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Intrabeam Scattering in the Tevatron Collider Upgrade

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1. INTRODUCTION

This report explores the effects of intrabeam scattering on the integrated luminosity for some conditions under consideration for the early stages of the Tevatron collider upgrade. This report concludes that intrabeam scattering effects, although they are hoped to become clearly visible, are not expected to wash out gains made by lowering β^* and emittances.

It is not the intent of this report to provide a physics tutorial on intrabeam scattering. However, a bibliography is provided at the end of this report which may be of use in that regard.

2. OVERVIEW USING IBSMT

In this section we present an overview of intrabeam scattering as it pertains to the Tevatron upgrade.

2.1 Range of Emittances

The range of emittances is chosen to include the values expected in the early stages of the Fermilab upgrade. The longitudinal emittance ranges from 1 to 4 eV-sec and the 95% normalized transverse emittance ranges from 6 to 24 π mm-mrad. Figure 1 shows the intrabeam scattering emittance growth rates for this range of emittances, an average Tevatron lattice, a beam energy of 1 TeV, an rf voltage of 1 MV/turn, and assuming 6E10 particles in a bunch. Table I gives the values. In this report, a growth rate $1/\tau$ is defined by:

$$\frac{1}{\tau} \quad \frac{d\epsilon/dt}{\epsilon} \quad . \tag{1}$$

The calculation is done for ϵ_x equal to ϵ_y. The figure demonstrates that the growth rates span two orders of magnitude for this modest range of emittances. τ_y is not listed in Table 1 since it is calculated to be of order 10 years which is insignificant.

These values are based on an asymptotic ($\gamma >> 1$) approximation to the Piwinski model[1] of intrabeam scattering. This particular approximation was developed by Alvin Tollestrup and Sekazi Mtingwa and has been coded into a computer program[2]. In this report it is referred to as IBSMT which stands for IntraBeam Scattering/Mtingwa and Tollestrup to distinguish it from other calculations of intrabeam scattering. IBSMT gives a choice on doing the Piwinski integrals. For the Tevatron collider there is not much difference in the choices as can be seen from Table I by comparing the columns labeled "approximate g(b)" and "more exact g(b)". This report uses the approximate g(b) choice.

2.2 Estimates of Emittance Growth Times

τ_x and τ_p from IBSMT can be estimated over the range of upgrade emittances by using:

$$\tau_{x,est} = 0.027\ \epsilon_x^{2.24}\ \epsilon_p^{0.68}\ \text{hours} \qquad \text{for 1 TeV} \tag{2a}$$

$$\text{1 MV/turn}$$

$$\tau_{p,est} = 0.103\ \epsilon_x^{1.23}\ \epsilon_p^{1.68}\ \text{hours.} \qquad \text{6E10 in the bunch} \tag{2b}$$

These do not represent a parameterization from IBSMT. Rather, they are presented here in this form in order to facilitate estimates of the effects of intrabeam scattering vis-a-vis projects such as bunched beam cooling. These show analytically how each τ depends on changes of emittances. Keep in mind that ϵ_x is always taken to be equal to ϵ_y in these estimates. This equalization of the transverse emittances is chosen in order to keep the intrabeam scattering models closely related to the real Tevatron, in which equalization of emittances is an operational fact. For the discussion of those cases in which they are unequal, one may return to Mtingwa/Tollestrup directly. Also, one should keep in mind that τ_x and τ_p scale directly with bunch intensity, so the leading constants in Eqs. 2 (0.027 and 0.103) are only appropriate for 6E10 in a bunch.

Figure 2 shows a comparison of these estimates to the IBSMT results. Figure 2a compares to the approximate IBSMT, and 2b compares to the exact IBSMT. The estimate does very well indeed. It should be obvious that the exponents and multiplicative constants will change if one changes the conditions: different IBS models, changes of energy and rf voltage, different range of τ_x and τ_p, etc. In addition, the multiplicative constant is inversely proportional to the number of particles in the bunch. Nevertheless, these simple estimates agree with IBSMT to better than 10% over the range of upgrade emittances under consideration even though the lifetimes cover two orders of magnitude. Thus, they can be used with confidence for quick estimates of the effects of intrabeam scattering in the Tevatron upgrade.

2.3 Estimates of Emittance Growth Rates

One may have noticed that the exponents in Eqs. 2a and 2b are related by a unit; that is, one could have written the estimates just as well with:

$$\tau_{x,est}/\epsilon_x = 0.027 \quad \epsilon_x^{1.24} \quad \epsilon_p^{0.68} \text{ hours} \tag{3a}$$

$$\tau_{p,est}/\epsilon_p = 0.103 \quad \epsilon_x^{1.24} \quad \epsilon_p^{0.68} \text{ hours} \; . \tag{3b}$$

Using the definition of growth rate from Eq. 1, one obtains an estimate for the emittance growth rates:

$$\frac{d\epsilon_{(x \text{ or } p),est}}{dt} = C \, \epsilon_x^{-1.24} \; \epsilon_p^{-0.68} \quad \text{with} \quad \begin{array}{l} C = 36.4\ \pi \text{ mm-mrad/hour for x} \\ C = 9.70 \text{ eV-sec/hour for p} \end{array} \tag{4}$$

Thus, one has obtained a very simple way to estimate the evolutionary path of emittances in a store.

From this, one can also write:

$$\frac{d\epsilon_x/dt}{d\epsilon_p/dt} = \frac{36.4\ \pi\ \text{mm-mrad}}{9.70\ \text{eV-sec}} \tag{5a}$$

or

$$d\epsilon_p = 0.266\ d\epsilon_x\ \frac{\text{eV-sec}}{\pi\ \text{mm-mrad}} \tag{5b}$$

This relationship between the differentials of the emittances means a plot of ϵ_p vs. ϵ_x would be a straight line as a store evolves if intrabeam scattering were the only consideration. This relationship is independent of the intensity.

3. INTEGRATED LUMINOSITY

3.1 Calculation

The integrated luminosities in this report are calculated by a computer program named ILUMI. It was originally written to perform the overlap integral as the bunches pass through one another as best as one can do to obtain the instantaneous luminosity. It takes into account the variation of the lattice functions through the interaction region. In addition it accounts for the finite bunch lengths as well as the increase of the horizontal beam size due to dispersion and momentum spread through the interaction region. The program has been updated to calculate integrated luminosities for a simulated store in the presence of intrabeam scattering, collision losses, and imperfect vacuum. A recent implementation of the program is named MECS (Model for Evolving Collider Stores), and was used at the Breckenridge Workshop, "Physics at Fermilab in the 1990's," (August 1989).

Figures 3 show integrated luminosities for a 10 hour store as calculated by ILUMI for four different conditions. Twelve starting points are represented in each figure corresponding to three transverse emittances (6, 12 and 24 π mm-mrad) and four longitudinal emittances (1, 2, 3 and 4 eV-sec). In all cases, intrabeam scattering is calculated according to the estimate to IBSMT given in Eq. 2. The program is told to step along in 6 minute intervals.

All figures have the following conditions:

- 1 TeV
- 6E10 protons and 3E10 pbars
- 6 bunches on 6 bunches
- 1 IR with 90 mbarns as the total cross section[3] .

The different conditions among the four figures are:

a. no horizontal/vertical coupling (no coupl)
b. horizontal/vertical coupling (ave coupl)
c. 2 π mm-mrad/hour emittance growth (2 pi/hr)
d. use ATC1 (50 cm β^*) or ATC17 (25 cm β^*) lattices[4] .

Collision loss is the only source of intensity decay considered in this report. Namely:

$$\frac{dN}{dt} = \frac{d\bar{N}}{dt} = R\,\sigma_c\,L/B \qquad (6)$$

with σ_c = total cross section
L = total luminosity at 1 IR
B = number of bunches in ring
R = number of (identical) interaction regions

The 2 π mm-mrad/hour empirical emittance growth rate (for both x and y) is based on an estimate from EXP-147 in which the emittance lifetimes were ~12 hours. It is included to demonstrate what happens when one is nowhere near intrabeam scattering effects-as was apparently the case during the first collider run in 1987. The amount of empirical emittance growth was reduced to about 0.3 π mm-mrad/hour for the second collider run in 1988-89[5] ; even so, this was still too much growth to allow the intrabeam scattering effects to manifest themselves.

Figures 3a to 3c show that the integrated luminosity is quite insensitive to the longitudinal emittance for the 50 cm lattice (ATC1). For the 25 cm lattice (ATC17), Fig. 3d shows that the effects of the longitudinal emittance become more and more apparent as the transverse emittance is reduced. Comparing Figs. 3b and 3d, one sees that one does not gain a factor of 2 in the integrated luminosity; rather the gain factor is between ~1.3 and ~1.6 depending on the initial emittances.

3.2 Incuding Coupling

The simplest intrabeam scattering models predict a growth of the longitudinal emittance, and a shrinking of both the horizontal and vertical emittances for the upgrade conditions. The first modification to the simplest intrabeam scattering models includes the horizontal dispersion in the lattice, which causes growth of the horizontal emittance. This is done for all the intrabeam scattering models referred to in this report.

However, EXP 147 shows that the horizontal and vertical emittances tend to be the same in the Tevatron, indicating the particle motion is coupled between the horizontal and vertical planes. This report reasonably assumes that this coupling takes place and reaches a steady state on a time scale much shorter than intrabeam scattering time scales.

During the coupling process, the transverse momentum is conserved:

$$\text{conserved} = p_T^2 \, (\theta_x^2 + \theta_y^2) \tag{7}$$

where the θ's represent the angles of the momentum vector projected onto the transverse xy plane. The (unnormalized, rms) transverse emittance is given by:

$$\epsilon = \frac{\sigma^2}{\beta}\pi = \frac{\sigma}{\beta}\sigma\pi \quad \text{or } \epsilon = \sigma'\sigma\pi \tag{8}$$

with σ = rms spatial beam size
and σ' = rms angular beam size
and β = lattice amplitude function

from which $\sigma' = \sigma/\beta$ and $\epsilon = \beta\,(\sigma')^2\pi$. (9)

Assuming $\beta_x = \beta_y = \beta$, the sum of the transverse emittances is:

$$\epsilon_x + \epsilon_y = \beta\,[\,(\sigma_x')^2 + (\sigma_y')^2\,]\pi \ . \tag{10}$$

If one identifies σ' with θ, then the quantity which is conserved during coupling is $\epsilon_x + \epsilon_y$.

Intrabeam scattering causes ϵ_x to grow. Coupling is assumed to cause this growth to be shared between the vertical and horizontal. For a steady state condition, $\epsilon_x = \epsilon_y$.

These coupling assumptions are put into ILUMI in the following manner. Both ϵ_x and ϵ_y start out equal. In time, pure intrabeam scattering alone would have caused ϵ_x to grow to a new value ϵ_{x1}, with ϵ_y remaining at its old value. This would give an emittance imbalance. Coupling removes this imbalance by equalizing the emittances; namely the average is taken:

$$\text{new } \epsilon_x = \text{new } \epsilon_y = \frac{\epsilon_{x1} + \text{old } \epsilon_y}{2} \tag{11}$$

This has a large impact on the transverse emittance growth rates. Firstly, it causes the vertical to grow. Secondly, it causes a slower horizontal growth than pure intrabeam scattering alone would have allowed by a factor of two. This smaller horizontal growth in turn leads to a faster growth of the longitudinal emittance than intrabeam scattering alone would have predicted.

3.3 Estimate of Coupling Effect on Integrated Luminosity

The net effect of coupling on the integrated luminosity is not very large as can be seen by comparing Figs. 3a and 3b. For the 24 and 12 π emittances it is not at all important, and for the 6 π emittance it is reduces the integrated luminosity by a few percent. This behavior can be made plausible by the following analytic argument. Assume the intensities do not decay and longitudinal effects can be ignored; then one can write:

$$\int L \, dt = \text{constant} \int_0^T \frac{dt}{\sqrt{\epsilon_x \, \epsilon_y}} = L_0 \int_0^T \frac{dt}{\sqrt{\dfrac{\epsilon_x}{\epsilon_{ox}} \, \dfrac{\epsilon_y}{\epsilon_{oy}}}} \quad . \tag{12}$$

For growth times τ which do not change very much over the course of a store of length T, one can write:

$$\epsilon_x(t) \simeq \epsilon_{ox}\left(1 + \frac{t}{\epsilon_{ox}} \frac{d\epsilon_x}{dt} \right) \text{ or } \epsilon_x(t) \,/\, \epsilon_{ox} \simeq 1 + t/\tau. \tag{13}$$

For the case of no coupling, ϵ_y does not change so the ratio ϵ_y/ϵ_{oy} is unity, and the time dependence in the radical in the integral reduces to:

$$1 + t/\tau \quad \text{for no coupling.} \tag{14}$$

For the case in which there is coupling, the growth time τ is cut in half, but both x and y increase at this new rate. This gives a time dependence in the radical in the integral of:

$$1 + t/\tau + (t/2\tau)^2 \quad \text{with coupling.} \tag{15}$$

Thus, one would expect to see effects of coupling in the integrated luminosity when the uncoupled horizontal emittance growth time is of order $\tau_x \simeq T/2$, or 5 hours. Figure 1 shows times of this order for emittances of 6 π but not for 12 or 24 π. This is in agreement with this analytic estimate.

4. EVOLUTION OF STORES

4.1 Luminosity and Lifetimes

Figures 4a-d show the luminosity and luminosity lifetime for the twelve starting conditions stated above as the store evolves. The four plots correspond to the four different conditions listed before Eq. 6.

Comparison of Figs. 4b and 4d demonstrate several results that can only be gotten from properly performing the overlap integral. For 6 π mm-mrad and 1 eV-sec the 50 cm lattice gives an initial luminosity of 7.93 E30 $cm^{-2}sec^{-1}$, whereas the 25 cm lattice gives 13.1 E30. The gain is 1.66 rather than 2. This "tax" is due to two effects which mix the longitudinal emittance with the lattice functions:

- The bunch length is the same in both cases, but β is increasing faster with the lower β^* as one moves away from the center of the IR.

- The momentum spread is the same in both cases, but the dispersion happens to be worse with the lower β^* lattice. (η,η') is (.0149 m,.0845) for ATC1 and (.0542 m,.1784) for ATC17.

For the 6 π mm-mrad 2 eV-sec case, the initial luminosity lifetimes are 5.64 hours for the 50 cm lattice and 4.23 hours for the 25 cm lattice. Using Eq. 6 one can calculate the partial lifetime due to particle loss: 46.7 hours for the 50 cm lattice and 28.3 hours for the 25 cm lattice. (These do scale with the luminosity.) Unfolding these, one calculates that the partial luminosity lifetime due to intrabeam scattering is 6.43 hours for the 50 cm lattice and 4.97 hours for the 25 cm lattice. These are not the same in spite of the fact that the initial intrabeam scattering growth rates have not changed. Again the reason for the difference is due to the mixing of the longitudinal emittance with the lattice functions.

4.2 Evolution of Intensities and Emittances

Figure 5 shows the evolution of the intensities and emittances during the store for protons. Figure 6 shows the results for antiprotons. The intensity losses for protons and antiprotons in a,b,c are identical since they are assumed to come from collisions only. The antiproton emittances grow less since there are fewer antiprotons in the bunch. One may choose to have the proton transverse beam size larger than the antiprotons to help reduce beam-beam effects.[6] (This became important in the second collider run in 1988-89.)

These figures show longitudinal emittances approaching 6 eV-sec. The bucket size[7] is calculated from:

$$\text{bucket} = \frac{16\ R}{\hbar\ c} \sqrt{\frac{eV\ E}{2\pi h\ \eta}}\ \text{eV-sec} \quad \text{with } \eta = \mid 1/\gamma_t^2 - 1/\gamma^2 \mid \tag{16}$$

For 1 TeV, 1 MV/turn and the SYNCH given in the Design Report[8], one obtains a bucket size of 10.7 eV-sec. To the extent that this is larger than 6 eV-sec, one is probably not in danger of losing particles out of the bucket due to intrabeam scattering alone.

<u>4.2.1 Growth times.</u> Figures 7 and 8 show τ_p vs. τ_H as calculated by ILUMI. The points are separated by one hour intervals. τ_H is the horizontal emittance lifetime. Do not confuse τ_H with τ_x; they are equal only in the case in which intrabeam scattering is the dominant consideration. This is the case for Fig. 7a in which the grid of Fig. 1 is overlayed to represent the starting values. The grid in Fig. 8a for the antiprotons is shifted by a factor of two since the antiproton intensity is half the proton intensity initially.

The grid from Fig. 1 which is overlayed on Figs. 7a and 8a also shows how far the estimate to IBSMT is being pushed. One may quibble about the fact that the growth times are getting outside the range of the fit. However, the emittances for which this occurs are for 24 π mm-mrad and 4 eV-sec, which only become important for the Main Injector upgrade. (There is a better approach to the problem in these cases, which is intended to be the subject of a later report on MECS.)

4.2.2 Horizontal and longitudinal emittances. Figures 9 and 10 are the follow up to the comment made after Eq. 5. Indeed, ϵ_p vs. ϵ_H does follow a straight line as the store proceeds when intrabeam scattering is the dominant consideration as Figs. 9a and 10a demonstrate. However, even when coupling is included, they still follow straight lines, as best as can be seen from the plots. Figures 9c and 10c show quite different behavior, but this is the case in which a 2 π mm-mrad/hour constant emittance growth is invented.

4.3 Initial Luminosities

Figure 11 shows the initial luminosities for the 50 cm (ATC1) and 25 cm (ATC17) upgrade lattices. One does not gain a factor of two with the lower β^*, but one does gain a factor between ~1.4 and ~1.6 depending on the initial emittances. This is simply the effect of the finite longitudinal emittance.

5. COMPARISON OF IBS MODELS

5.1 Comparison to Bjorken and Mtingwa

The IBSMT computer program uses average lattice functions. Tables IIa-c are the results of another model of intrabeam scattering which takes into account the variation of the lattice functions around the ring. This model will be called IBSBM in this report. These numbers were provided by Sekazi Mtingwa and are based on his work with Bjorken[9]. For historical reasons, IBSBM was run with γ=1000 rather than with 1 TeV.

Figures 12 show the dispersion and beta functions for the four lattices considered[10]. The low-β used during the early part of the 1987 collider run had a considerable dispersion mismatch as well as a beta mismatch as can be seen by comparing Figs. 12a and 12b. The 50 cm double low-β proposed for the upgrade eliminates the beta mismatch and greatly reduces the dispersion mismatch as can be seen in Fig. 12c. The 25 cm double low-β lattice begins to show a beta mismatch as can be seen in Fig. 12d.

Figure 13 uses IBSBM for three of the four lattices. It demonstrates that the differences in growth rates among the lattices occur mostly in τ_x to the level of

30%. The extreme excursion occurs for the lattice with the worst dispersion mismatch; namely, the one used during the early part of the 1987 collider run.

Figure 14 compares IBSBM with the fixed target lattice to IBSMT for the twelve cases represented by 1,2,3,4 eV-sec and 6,12,24 π mm-mrad. Here, the differences are up to a factor of ~2.7 in τ_p and ~30% in τ_x. IBSBM always predicts a faster growth of the emittances than IBSMT predicts.

5.2 CERN Luminosity Lifetime

In 1983 Gareyte[11] reported that CERN's luminosity lifetime was $\tau \simeq 16$ hours which resulted from:

$$\frac{1}{\tau} = \frac{1}{\tau_p} + \frac{1}{\tau_{pbar}} + \frac{1}{\tau_\epsilon} \qquad \text{with } \tau_p = 60 \text{ hours, } \tau_{pbar} = 40 \text{ hours and } \tau_\epsilon = 50 \text{ hours} \tag{17}$$

Later in the same conference, Evans [LE2] showed that the proton intensity and horizontal emittance lifetimes agree well with intrabeam scattering predictions. The proton lifetime was dominated by protons leaving the rf buckets since intrabeam scattering increases the longitudinal emittance and the protons cross the separatrix of the 300 MHz buckets. They have since undertaken a program to decrease the rf frequency[12] in order to have larger buckets.

For the Fermilab upgrade conditions, the bucket is ~11 eV-sec, and the longitudinal emittances are expected to be ~ 6 eV-sec from intrabeam scattering late in a store. Thus, one does not expect Fermilab to have the same degree of difficulty from intrabeam scattering that was experienced at CERN with the particles streaming across the separatrix as the longitudinal emittance increased. If the Fermilab buckets were to be made small enough to allow particles to escape, there is a good possibility that the backgrounds at the experiments would begin to present a major problem which would have to be solved.

5.3 IBSLE Reference

The intrabeam scattering model provided by Lyndon Evans will be called IBSLE in this report. The big advantage of this model is that it can be done on a hand calculator. Both IBSLE and IBSMT have the same basic assumptions, but IBSMT allows the horizontal and vertical emittances to differ.

In calculating intrabeam scattering rates or lifetimes, one must keep in mind whether one is referring to amplitudes or emittances. There is a factor of two between them in growth rates as can be seen from:

$$\epsilon_x = \beta\gamma\ \sigma_x^2/\beta_x \quad \text{definition of transverse rms emittance} \tag{18}$$

from which

$$\frac{1}{\epsilon_x}\frac{d\epsilon_x}{dt} = \frac{2}{\sigma_x}\frac{d\sigma_x}{dt} \quad \text{which gives} \quad \frac{1}{\tau_{\epsilon_x}} = \frac{2}{\tau_{\sigma_x}} \quad \text{or} \quad \tau_{\sigma_x} = 2\ \tau_{\epsilon_x} \tag{19}$$

Thus, the emittance growth rate is twice the amplitude growth rate, or, equivalently, the amplitude lifetime is twice the emittance lifetime. This is the reason for the factor of 2 appearing in many of the figures and tables in this report.

Tables III and IV give the various definitions that Evans uses. The IBSLE factors in Table IV are defined in the lab frame. The difference between using the factor 16 ([LE1] and [LE3]) or 8 ([LE2]) in Table III is the factor of two that comes from referring to amplitude or emittance.

One additional comment about [LE3] in Table III is in order. In the brackets, [LE3] has Euler's constant alone, rather than divided by 2 as in [LE1] and [LE2]. Starting from [AP] and performing the Piwinski integral using the assumptions in any of the [LE] references, one arrives at Euler's constant divided by 2. So one concludes that [LE3] has a typo. But the difference is not at all important for the Tevatron since the factor ln(c/2a) is of order 25 and Euler's constant ≃0.58. For example:

$\beta\gamma = p/m \simeq 1066 \qquad Q \simeq 19.4 \qquad \beta_H \simeq 50$ meters

$$\text{give } \ln(c/2a) = 25.96 \text{ for } \epsilon = 16 \times 10^{-6}\,\text{m} = 24\ \pi \text{ mm-mrad for Fermilab convention} \tag{20a}$$

$$\text{and } \ln(c/2a) = 26.31 \text{ for } \epsilon = 4 \times 10^{-6}\,\text{m} = 6\ \pi \text{ mm-mrad for Fermilab convention} \tag{20b}$$

5.4 Numerical Examples Using IBSLE

5.4.1 Which emittance blows up faster? Using IBSLE one obtains a very simple expression which indicates which emittance blows up faster. This ratio does not depend on what convention one uses for the emittances as long as one is consistent:

$$\frac{\tau_H}{\tau_p} = \frac{\pi\ m\ Q}{\beta\ c\ Q_s}\ \frac{\epsilon_H}{\epsilon_L} \simeq .268\ \frac{\epsilon_H\ (\pi\ \text{mm-mrad})}{\epsilon_L\ (\text{eV-sec})} \tag{21}$$

for typical Fermilab values of $Q = 19.4$ and $Q_s = 7.13 \times 10^{-4}$ (corresponding to $f_{\text{synchrotron}} = 34$ Hz)

For example, with $\epsilon_H = 24\ \pi$ mm-mrad and $\epsilon_L = 3$ eV-sec (which represent Fermilab 95% emittances in the TeV I Design Report) one obtains $\tau_H/\tau_L = 2.14$. This indicates that the transverse growth time is greater than the longitudinal, so the longitudinal phase space would tend to increase faster.

5.4.2 Comparison of emittance evolution to estimate of IBSMT. One can also write the above as:

$$\epsilon_L/\tau_p = 0.268\ \epsilon_H/\tau_H \tag{22}$$

Then, using the definition of growth time, one arrives at:

$$d\epsilon_L/dt = 0.268\ d\epsilon_H/dt, \tag{23}$$

and finally,

$$d\epsilon_L = 0.268\ d\epsilon_H\quad . \tag{24}$$

This is to be compared to Eq. 5b:

$$d\epsilon_p = 0.266\ d\epsilon_x \text{ using IBSMT estimates}\quad . \tag{25}$$

Thus the evolution of the emittances during a store is predicted to be reassuringly the same using either the estimate to IBSMT or IBSLE.

5.4.3 Upgrade example using IBSLE. The example used here is for 1 TeV, 1MV/turn, 6E10 particles in a bunch, and 12 π mm-mrad and 2 eV-sec, in the

Fermilab convention. Converted to the CERN convention, these become 8 π mm-mrad and 4/3 eV-sec. The IBLSE factors from Table IV are:

$$A = 4.642 \times 10^{-10}\ \text{sec}^{-1},\ \ln(c/2a) = 11.42,\ k = 1.607 \tag{26a}$$

$$d^2 = 0.384,\ \text{and}\ a = 1/88.63. \tag{26b}$$

The synchrotron frequency is calculated[13] to be 34 Hz from:

$$f_s = \frac{1}{2\pi}\frac{hc}{R}\sqrt{\frac{\eta}{E}\frac{eV}{2\pi h}} \qquad \begin{array}{l} \text{with } h = 1113,\ R = 1\text{km},\ V = 1\text{MV},\ 1\ \text{TeV} \\ \eta = |\ 1/\gamma_t^2 - 1/\gamma^2\ | = 2.85 \times 10^{-3} \\ \text{for } \gamma_t = 18.74 \end{array} \tag{27}$$

The growth rates are τ_x = 10.0 hours and τ_p = 6.24 hours for 6E10 in a bunch.

5.5 Spot Check Comparison of IBS Models

The following table compares the three intrabeam scattering models referred to in this report for the case of 1 TeV, 1 MV/turn, 12 π mm-mrad, 2 eV-sec, and 6E10 in a bunch:

	τ_x	τ_p	
	hours		
IBSMT	11.2	6.75	
IBSBM	9.1	2.7	fixed target lattice
"	7.3	2.6	50 cm ATC1 upgrade lattice
IBSLE	10.0	6.24	

The different models predict intrabeam scattering growth times to be the same to within a factor of 1.5 for τ_x and 2.6 for τ_p. The 10% difference between IBSMT and IBSLE is a discrepancy since the underlying assumptions are the same.

6. COMMENTS AND CONCLUSIONS

The intent of this report is to concentrate on the impact of intrabeam scattering on the Tevatron. There are several other effects which are ignored in this report which do reduce the integrated luminosity. Beam gas interactions reduce the intensities of both beams as well as increase their transverse emittances, and this would decrease the integrated luminosity. In intrabeam scattering, the bunches are assumed to be independent and the lattice they experience is assumed to be linear. However, beam-beam interactions, whether head-on near the interaction regions or longer range in the arcs with separated orbits, must be considered also. For example, in the head-on case, if the protons are more intense but have a smaller transverse emittance than the antiprotons, then the antiproton emittance may grow at a rate larger than intrabeam scattering predicts. This would reduce the integrated luminosity. The proton and antiproton intensities decrease to some level due to particles streaming out of the rf buckets. EXP-147 shows bunch intensity lifetimes of ~190 hours for protons and ~125 hours for the antiprotons during one store of the 1987 collider run. So one might be led to conclude that it was (and will) not be an important consideration in the upgrade luminosity lifetime. However, this may need more careful analysis, particularly if one considers upgrading the rf.

There are other effects which are insignificant for the Tevatron but which are important for other machines. One example is radiation damping in the SSC.[14] This causes the luminosity to increase (on paper) for about 24 hours after a store begins. Another effect which has been ignored in the calculation is bunched beam cooling in the Tevatron.[15] The successful implementation of this technique will very significantly increase the integrated luminosity available for the Fermilab colliding detector experiments.

In conclusion, even though the growth times associated with intrabeam scattering are alarmingly brief at first glance, the impact on the integrated luminosity is not nearly as dramatic after a full analysis of the situation is performed.

Table I. IBSMT Intrabeam Scattering Growth Times

All τ's are in hours, N = 6E10, E = 1 TeV, 1 MV/turn rf voltage
ϵ_T = normalized 95% transverse emittance (π mm-mrad)
ϵ_p = longitudinal emittance (eV-sec)

		approximate g(b)		more exact g(b)	
ϵ_T	ϵ_p	$2\tau_x$	$2\tau_p$	$2\tau_x$	$2\tau_p$
6	1	2.9	1.8	2.877	1.649
12	1	14.3	4.3	14.08	4.037
24	1	73.0	11.1	71.93	10.31
6	2	4.8	5.9	4.712	5.404
12	2	22.3	13.5	21.86	12.54
24	2	109.1	33.0	107.2	30.75
6	3	6.6	12.1	6.462	11.12
12	3	29.7	27.0	28.98	24.93
24	3	140.6	63.9	137.9	59.32
6	4	8.4	20.4	8.178	18.76
12	4	36.8	44.5	35.83	41.09
24	4	170.1	103.0	166.6	95.51

Tables II. IBSBM Intrabeam Scattering Growth Times

(FROM BJORKEN-MTINGWA)
All τ's are in hours, N = 6E10, γ = 1000, 1 MV/turn rf voltage
ϵ_T = normalized 95% transverse emittance (π mm-mrad)
ϵ_p = longitudinal emittance (eV-sec)

Table IIa. Fixed Target Lattice

ϵ_T	ϵ_p	$2\tau_p$	$2\tau_x$	τ_y
6	1	.703E+00	.234E+01	-.133E+05
12	1	.182E+01	.118E+02	-.679E+05
24	1	.488E+01	.625E+02	-.360E+06
6	2	.217E+01	.374E+01	-.206E+05
12	2	.543E+01	.181E+02	-.102E+06
24	2	.142E+02	.927E+02	-.528E+06
6	3	.432E+01	.505E+01	-.273E+05
12	3	.106E+02	.238E+02	-.131E+06
24	3	.271E+02	.119E+03	-.667E+06
6	4	.702E+01	.630E+01	-.336E+05
12	4	.169E+02	.291E+02	-.159E+06
24	4	.427E+02	.142E+03	-.793E+06

Table IIb. DEJB0-1987 lattice
low-β used in 1987

ϵ_T	ϵ_p	$2\tau_p$	$2\tau_x$	τ_y
6	1	.730E+00	.165E+01	-.147E+05
12	1	.188E+01	.807E+01	-.727E+05
24	1	.500E+01	.415E+02	-.377E+06
6	2	.226E+01	.273E+01	-.235E+05
12	2	.564E+01	.128E+02	-.112E+06
24	2	.147E+02	.632E+02	-.561E+06
6	3	.449E+01	.375E+01	-.317E+05
12	3	.110E+02	.171E+02	-.146E+06
24	3	.281E+02	.824E+02	-.719E+06
6	4	.727E+01	.473E+01	-.395E+05
12	4	.176E+02	.212E+02	-.178E+06
24	4	.443E+02	.100E+03	-.862E+06

Table II continued. IBSBM Intrabeam Scattering Growth Times

(FROM BJORKEN-MTINGWA)
All τ's are in hours, N = 6E10, γ = 1000, 1 MV/turn rf voltage
ϵ_T = normalized 95% transverse emittance (π mm-mrad)
ϵ_p = longitudinal emittance (eV-sec)

Table IIc. ATC1 Upgrade Lattice
(2 IR's with 50 cm β^*)

ϵ_T	ϵ_p	$2\tau_p$	$2\tau_x$	τ_y
6	1	.680E+00	.188E+01	-.140E+05
12	1	.176E+01	.936E+01	-.705E+05
24	1	.469E+01	.490E+02	-.370E+06
6	2	.210E+01	.306E+01	-.221E+05
12	2	.527E+01	.146E+02	-.107E+06
24	2	.137E+02	.733E+02	-.546E+06
6	3	.419E+01	.417E+01	-.293E+05
12	3	.103E+02	.193E+02	-.139E+06
24	3	.263E+02	.946E+02	-.694E+06
6	4	.680E+01	.524E+01	-.362E+05
12	4	.164E+02	.238E+02	-.168E+06
24	4	.414E+02	.114E+03	-.828E+06

Table III. IBSLE Growth Rates.

In [LE1] and [LE3], intrabeam scattering is expressed in terms of emittance growth rates.

From [LE1]:

$$\frac{1}{\tau_x} = \frac{16\pi^2 A}{a} d^2 \left[\ln(c/2a) - \bar{\gamma}/2 \right]$$

$$\frac{1}{\tau_p} = \frac{16\pi^2 A}{a} (1 - d^2) \left[\ln(c/2a) - \bar{\gamma}/2 \right]$$

From [LE3]:

$$\frac{1}{\tau_H} = \frac{1}{\epsilon_H} \frac{d\epsilon_H}{dt} = \frac{16\pi^2 A}{a} d^2 \left[\ln(c/2a) - \bar{\gamma} \right]$$

$$\frac{1}{\tau_p} = \frac{1}{\epsilon_p} \frac{d\epsilon_p}{dt} = \frac{16\pi^2 A}{a} (1 - d^2) \left[\ln(c/2a) - \bar{\gamma} \right]$$

In [LE2], intrabeam scattering is expressed in terms of amplitude growth rates:

$$\frac{1}{\sigma_{x'}} \frac{d\sigma_{x'}}{dt} \simeq \frac{8\pi^2 A}{a} d^2 \left[\ln(c/2a) - \bar{\gamma}/2 \right]$$

$$\frac{1}{\sigma_p} \frac{d\sigma_p}{dt} \simeq \frac{8\pi^2 A}{a} (1 - d^2) \left[\ln(c/2a) - \bar{\gamma}/2 \right]$$

Table IV. IBSLE Factors.

$$A = \frac{N r_p^2 m}{\pi\beta\gamma\epsilon_H\epsilon_V\epsilon_L}$$

m = proton rest mass (938.28 MeV)

r_p = classical proton radius (1.535×10^{-18}m)

N = number of protons in the bunch

$\beta\gamma$ = momentum/mass

$\epsilon_H = \epsilon_x$ = horizontal emittance defined at "2σ"

$= \frac{4\beta\gamma}{\beta_H}\sigma_H^2$ for rms beam size σ_H at β_H

$= 4\beta\gamma\beta_x\sigma_x^2$, for rms beam divergence σ_x, at β_x

ϵ_L = longitudinal emittance defined at $2\sigma_E$

$$d^2 = 1/(1+k)$$

$$k = \frac{\pi m Q \epsilon_H}{\beta c Q_s \epsilon_L}$$

Q = betatron tune

c = speed of light (2.998×10^8 m/s)

βc = particle speed

Q_s = synchrotron tune

$$a = \frac{Q}{\gamma\sqrt{1+k}}$$

$$c/2a = \left[\frac{\beta\gamma}{\epsilon_H\beta_H}\right]^{1/4} \frac{\epsilon_H}{2\sqrt{2\ r_p}}$$

$\bar{\gamma} = 0.5772157\ldots$ (Euler's constant)

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[JG] J. Gareyte, Proceedings of the 12th International Conference on High-Energy Accelerators (Fermilab, 1983), p. 17.

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[LE3] L. Evans, Physics of Particle Accelerators (SLAC Summer School 1985 and Fermilab Summer School 1984), AIP Conference Proceedings No. 153, 1987, p. 1723.

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FOOTNOTES AND REFERENCES

1. A. Piwinski, Proceedings of the 9th International Conference on High-Energy Accelerators (Stanford, 1974), p. 405.

2. A. Tollestrup and S. Mitingwa, "Intrabeam Scattering Formulae for the Tevatron Upgrade," UPC-177, Fermilab internal report.

3. This is based on a rather large extrapolation of the graph on p159 of the 1984 Particle Properties Data Booklet. E710 has published the value of 78.3±5.9 mb for 900 GeV on 900 Gev; N. A. Amos, et al., Physical Review Letters, 63, 2784 (1989).

4. The acronym ATC1 stands for "Altered Tom Collins" lattice, step 1. The translation is "50 cm β^* at B0 and D0". ATC17 is step 17 which means 25 cm β^*'s.

5. "Calculation of Integrated Luminosity for Beams Stored in the Tevatron Collider," D. A. Finley, IEEE 1989 Part. Accel. Conf., Chicago, (March 1989).

6. Tom Collins, Fermilab; Nikolai Dikansky and Dmitri Pestrikov, INP, Novosibirsk; private communications, 1987.

7. TM-1381 "The Beam and the Bucket", Sho Ohnuma, January 22, 1986.

8. A Report on the Design of the FNAL Superconducting Accelerator, May 1979.

9. J. D. Bjorken and S. K. Mtingwa, Particle Accelerators, 13, 115 (1983).

10. The SYNCH output for these lattices may be found in the VAX area called ALMOND::USR$DISK4:[FINLEY.PUBLIC]name.OUT. The names are FIXEDTARGET, DEJB01987, ATC1DF and ATC17DF

11. J. Gareyte, Proceedings of the 12th International Conference on High-Energy Accelerators (Fermilab, 1983), p. 17.

12. Helen Edwards, Fermilab, now at SSCL, private communication.

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14. Private communicagion, David E. Johnson of the SSC at the Breckenridge Workshop, August 1989.

15. Gerald P.Jackson, Fermilab Wilson Fellowship Project.

APPENDIX ON LUMINOSITY CALCULATIONS

INTRODUCTION

Herein is contained a description of luminosity calculations based on a computer program written with the Tevatron in mind. The program in turn is based on a write-up by Mel Month dated June 1, 1985 and entitled Collider Performance with Ideal Collisions (Accel. Div. Report 85-1; D0 Note 201). The original motivation for writing this program was to address the question "Suppose the dispersion is not zero through a low-β interaction region?". I've organized this description in two parts. In the first part, I repeat those parts of Mel's writeup which I have used and list the general assumptions made in the calculations. I've tried to keep the assumptions clearly distinguished from the arbitrary choices. The former effect the physical relevance of the calculation, the latter do not. The second part contains mathematical notes, and some relevant definitions and estimates.

1. GENERAL ASSUMPTIONS

In this section I list the assumptions of a general nature which should not compromise the calculation of luminosity for conditions achievable with the Tevatron. This section finishes with a specific expression for the luminosity which involves integrals to be done by the program.

1.1 General Assumptions 0

The first page of Mel's write-up contains the statement:

"The luminosity is a relativistic invariant, and can be expressed by the overlap integral,

$$L = c \quad [\ |\beta_1 - \beta_2|^2 - |\beta_1 x \beta_2|^2 \ ]^{1/2} \int \rho(1)\rho(2) dV \ ,$$

where $\rho(1)$ and $\rho(2)$ are volume particle densities, β_1 and β_2 are particle velocities in units of the velocity of light, c, and dV is the space differential,

$$dV = dx \ dy \ dz \ ."$$

The above form requires:

General Assumption 0a: All the particles described by $\rho(i)$ have the same speed.

In addition, I impose:

General Assumption 0b: The particles are grouped in bunches.

These two assumptions are incompatible in the Tevatron at some level due to the momentum sread within a bunch. I declare this incompatibility to be insignificant and move on to:

General Assumption 0c: The rf harmonic number is 1113 for both types of colliding bunches.

General Assumption 0d: We are colliding protons and antiprotons. (Just in case you need reminding.)

1.2 General Assumption 1

Mel chose a coordinate system such that the bunches are moving in the z-direction. I further specify the coordinate system to be at rest relative to Fermilab, and put the origin at either TeV B0 or TeV D0.

General Assumption 1 is: the collisions are "head-on" between equal speed bunches; that is:

$$\beta_1 = - \beta_2 \ .$$

This results in the expression collapsing to the form:

$$L = 2 \ \beta c \ \int \rho(1)\rho(2) dV \ .$$

1.3 General Assumptions 2

Since the bunches are moving in our coordinate system, the ρ's are a function of time. Consequently L is a function of time. I'll temporarily write it as L(t), until I integrate out the time dependence. Following Mel's lead (but making fewer assumptions about ρ) I make:

General Assumption 2a: the particle densities can be written as:

$$\rho_i(x,y,z,t) = N_i \ S_i(x,y,z) \ T_i(z-\delta_i) \ .$$

T_i contains the time dependence and is dimensionless. δ_i is $\pm \beta c(t - t_i)$, where t_i is the time when the center of the bucket containing bunch i reaches z=0. The ± sign signifies which bunch is moving in which direction.

Strictly speaking, the buckets in the Tevatron only exist near F0, so when I use the word "bucket" in the context of an interaction region I really mean "the image of the bucket travelling with the bunch".

I choose the origin of time to be the instant at which the center of bucket 1 crosses z=0; this means t_1=0. Thus, for the Tevatron, type 1 is identified with protons and type 2 with antiprotons. I choose the protons to move in the +z direction. Also, one can identify $\beta c t_2$ as the distance the antiprotons should be moved to be properly cogged.

N_i is the total number of particles in a bunch which brings us to:

General Assumption 2b: N_i is a constant; this is implicit in the above expression, but explicit mention is merited.

1.4 General Assumptions 3

On the second and third pages of Mel's write-up he says:

"Substitute ... [ρ_i and δ_i] ... into the general expression for the luminosity to obtain the instantaneous luminosity, L(t). Then, integrate over time as the bunches pass through each other to find the luminosity per bunch collision, L_B (cm^{-2}):

$$L_B = \int_{-\infty}^{\infty} L(t) \ dt \ ."$$

Combining this with the assumptions made so far results in:

$$L_B = 2 \ \beta c \ N_1 \ N_2 \int dt \ T_1 \ T_2 \int dV \ S_1 \ S_2 \ .$$

General Assumption 3a is: The accelerator is DC; this means we have stationary buckets.

General Assumption 3b is: Each particle density is insignificant outside the length of its stationary bucket. This allows me to confine the time integral to the duration it takes for the buckets to pass through one another. In addition, it allows me to confine the z part of the space integral to the length of a stationary bucket. This means no satellite bunches are counted in the calculation of the luminosity.

1.5 General Assumptions 4

General Assumption 4a is: When a bunch returns to the interaction region after orbiting in the Tevatron, the particle density returns unchanged. This allows me to write the luminosity in its more familiar form:

$$L = B\ f\ L_B\ .$$

Here, B is the number of buckets containing colliding bunches, and f is the revolution frequency. In writing this, I have made:

General Assumption 4b: B is the same for protons and antiprotons.

General Assumption 4c: N_1 is the same for all B proton bunches and N_2 is the same for all B antiproton bunches.

General Assumption 4d: There are B identical passages through the interaction region per turn.

1.6 Specific Expression for the Luminosity

With these general assumptions, we have finally arrived at what I'll refer to as the specific expression for the Tevatron luminosity:

$$L = 2\ B\ N_1\ N_2\ f\ \beta c \int dt\ T_1\ T_2 \int dV\ S_1\ S_2\ .$$

These are the integrals which the program must perform.

2. MATHEMATICAL NOTES

2.1 Accuracy vs. Patience

The acceptance, a, is defined in terms of the full width of the beam, W, at which the lattice amplitude function is β:

$$a = (W/2)^2 \pi / \beta .$$

The normalized emittance, ϵ, is defined at Fermilab in terms of the second moment of the beam profile distribution, σ:

$$\epsilon = 6(p/m) \sigma^2 \pi / \beta$$

These can be combined to yield an expression for W in terms of σ:

$$W = 2 [(a/\epsilon) (6p/m)]^{1/2} \sigma$$

The granularity of the calculation, ΔW, can be characterized either in terms of W and the number of segments, N, as:

$$\Delta W \equiv W/N = (2/N) [(a/\epsilon) (6p/m)]^{1/2} \sigma ,$$

or in terms of σ and a fraction, f, as:

$$\Delta W \equiv f \sigma = (2/N) [(a/\epsilon) (6p/m)]^{1/2} \sigma .$$

N and f are related by the expression:

$$N = (2/f) [(a/\epsilon) (6p/m)]^{1/2} .$$

You want f to be "small" in order to keep the calculation of the integral accurate. You also want N to be "small" in order to keep your patience as the calculation proceeds. Thus, you have to reach a compromise. A numerical example appropriate to "yet-to-be-achieved Tevatron conditions" should help at this point:

$a = 1 \pi$ mm-mrad, $\epsilon = 10 \pi$ mm-mrad, $p = 1000$ GeV, gives

$N = 50.6 / f$

If I choose f = 0.25, then N = 202.

The program allows N to be as large as 501. Whether this is adequate or not depends on whether the results of the calculation depends on the choice of f.

2.2 Handling Gaussians

From the definition of a Gaussian:

$$(2\ \pi)^{1/2}\ \sigma = \int dx\ \exp(-x^2/2\sigma^2)\ .$$

Suppose:

$$Y(\sigma_1,\sigma_2) = \int dy\ \frac{\exp(-y^2/2\sigma_1^{\ 2})}{(2\ \pi)^{1/2}\ \sigma_1}\ \frac{\exp(-y^2/2\sigma_2^{\ 2})}{(2\ \pi)^{1/2}\ \sigma_2}\ .$$

Then:

$$Y(\sigma_1,\sigma_2) = \frac{1}{(2\ \pi)^{1/2}\ [\ \sigma_1^{\ 2} + \sigma_2^{\ 2}\ ]^{1/2}}\ .$$

Suppose:

$$dL/dz \sim \int dt\ \exp[-(z\text{-}ct)^2/2\sigma^2]\ \exp[-(z+ct)^2/2\sigma^2]\ .$$

Then:

$$dL/dz \sim \exp(-z^2/\sigma^2)\ .$$

2.3 Crossing Angle

For the Tevatron, just how good is the approximation:

$$[\ |\beta_1\ \text{-}\beta_2|^2\ \text{-}\ |\beta_1 x \beta_2|^2\ ]^{1/2} \equiv b \simeq 2\ \beta?$$

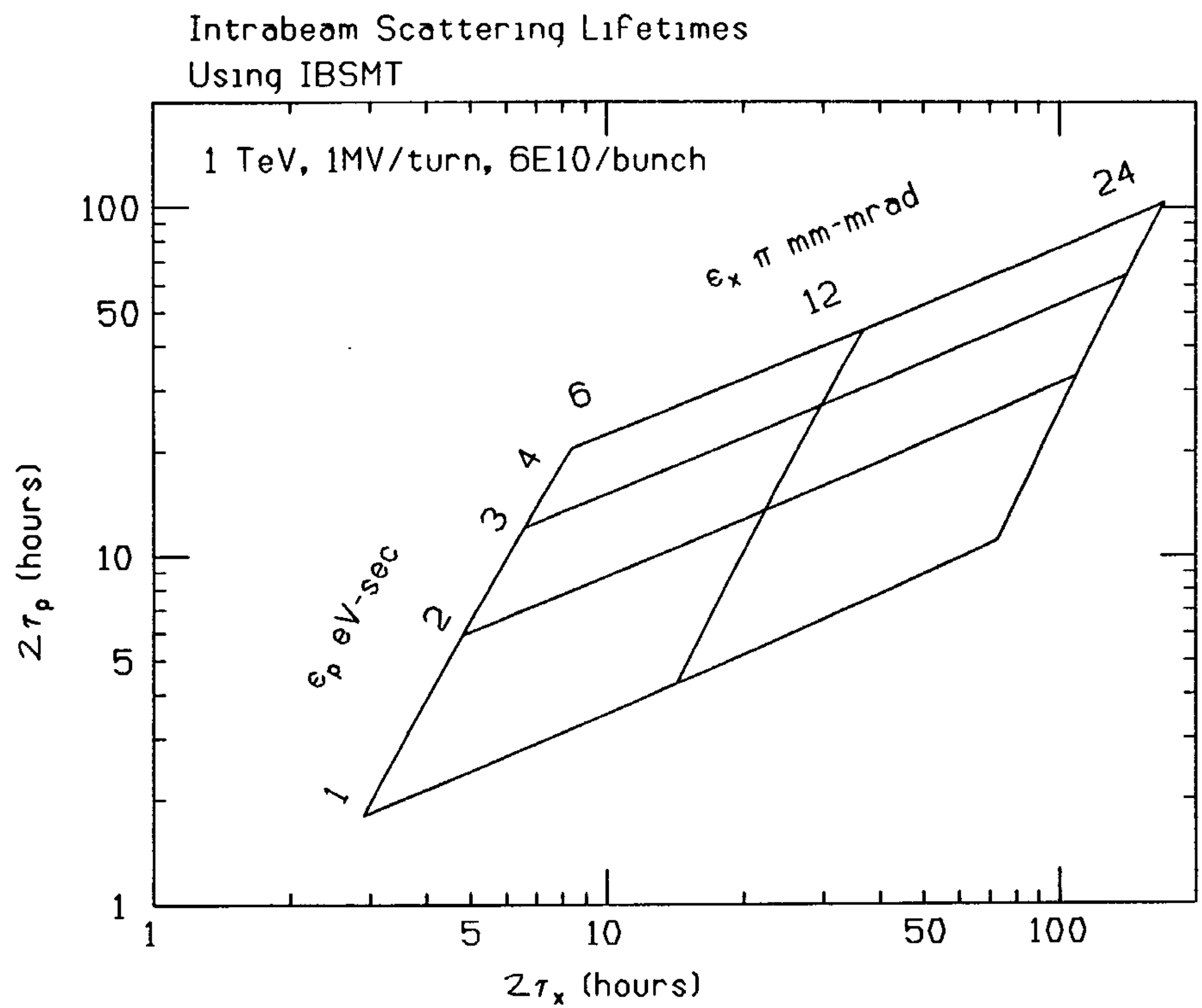
Consider this case. Particle 1 exits one of the inner low β quads at the very top of the beam tube, passes through the interaction region, and enters the other inner low β quad at the very bottom of the beam tube. Particle 2 follows a trajectory taken in the opposite sense. The angle between the trajectories is $\theta = \pi - \epsilon$.

This is a conservative case because particles with such trajectories could not circulate due to the anti-symmetric quad steering in any Tevatron straight section insert.

Take the diameter of the beam tube to be 2 7/8 inches, and the distance between the quads to be 15.2 meters. This means ϵ is about 4.79 mrad.

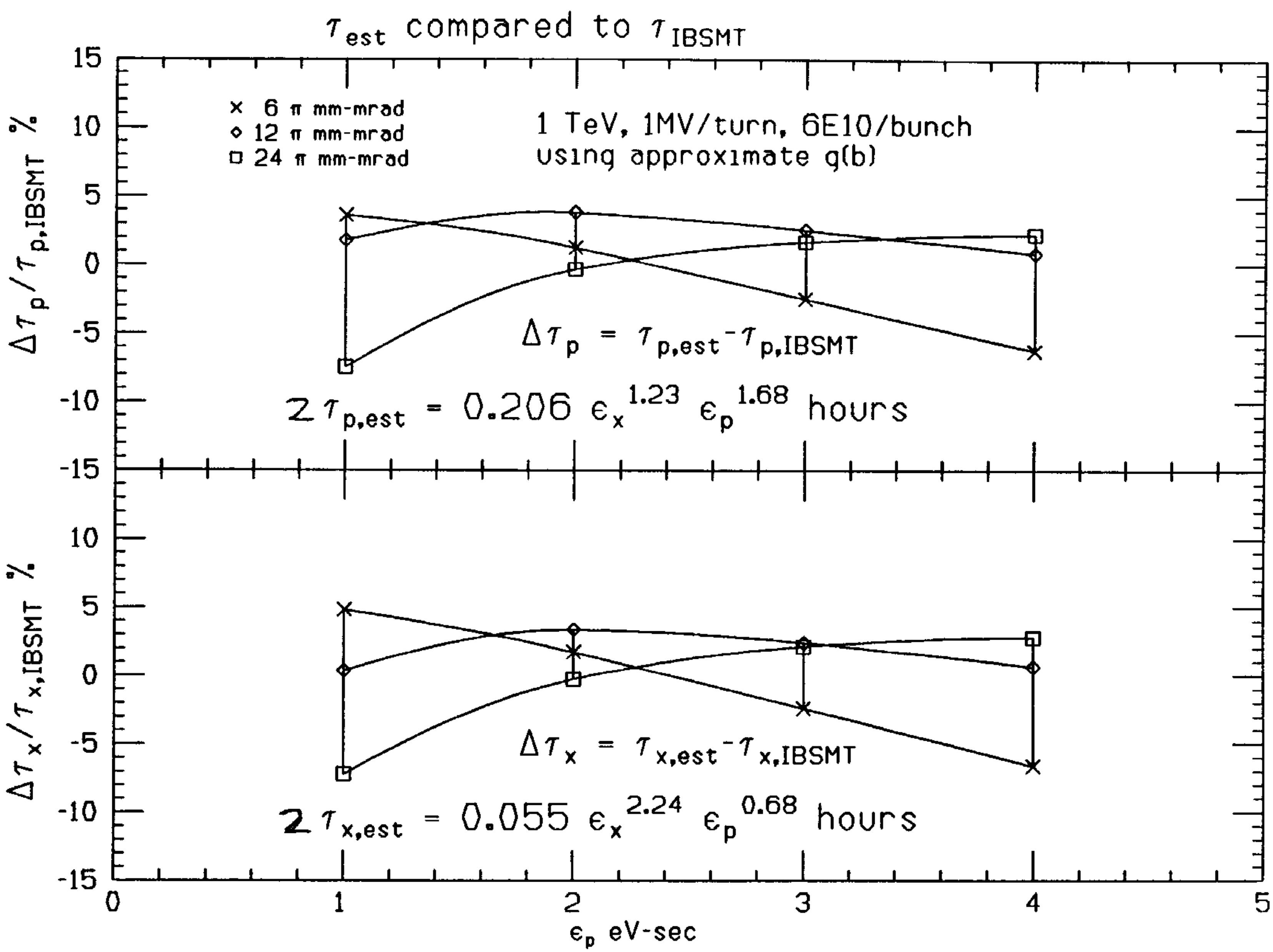
For these conditions, b is equal to 2 β to within 0.00058%.

If a decision is made to know it better than this, I volunteer to criticize the decision.



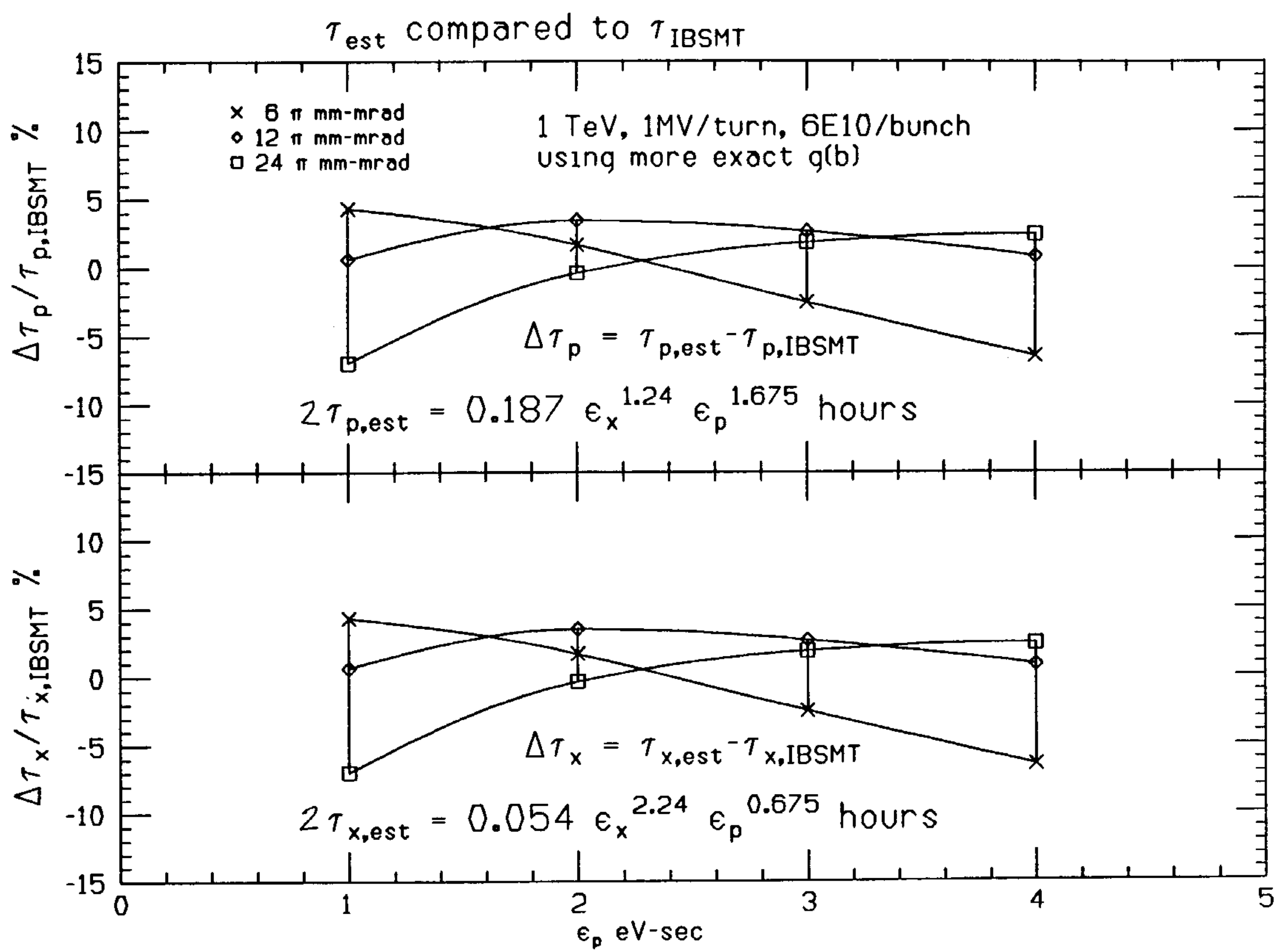
Intrabeam Scattering Lifetimes
Using IBSMT
1 TeV, 1MV/turn, 6E10/bunch
ϵ_x π mm-mrad
6
12
24
ϵ_p eV-sec
1
2
3
4
$2\tau_p$ (hours)
1
5
10
50
100
$2\tau_x$ (hours)

Figure 1



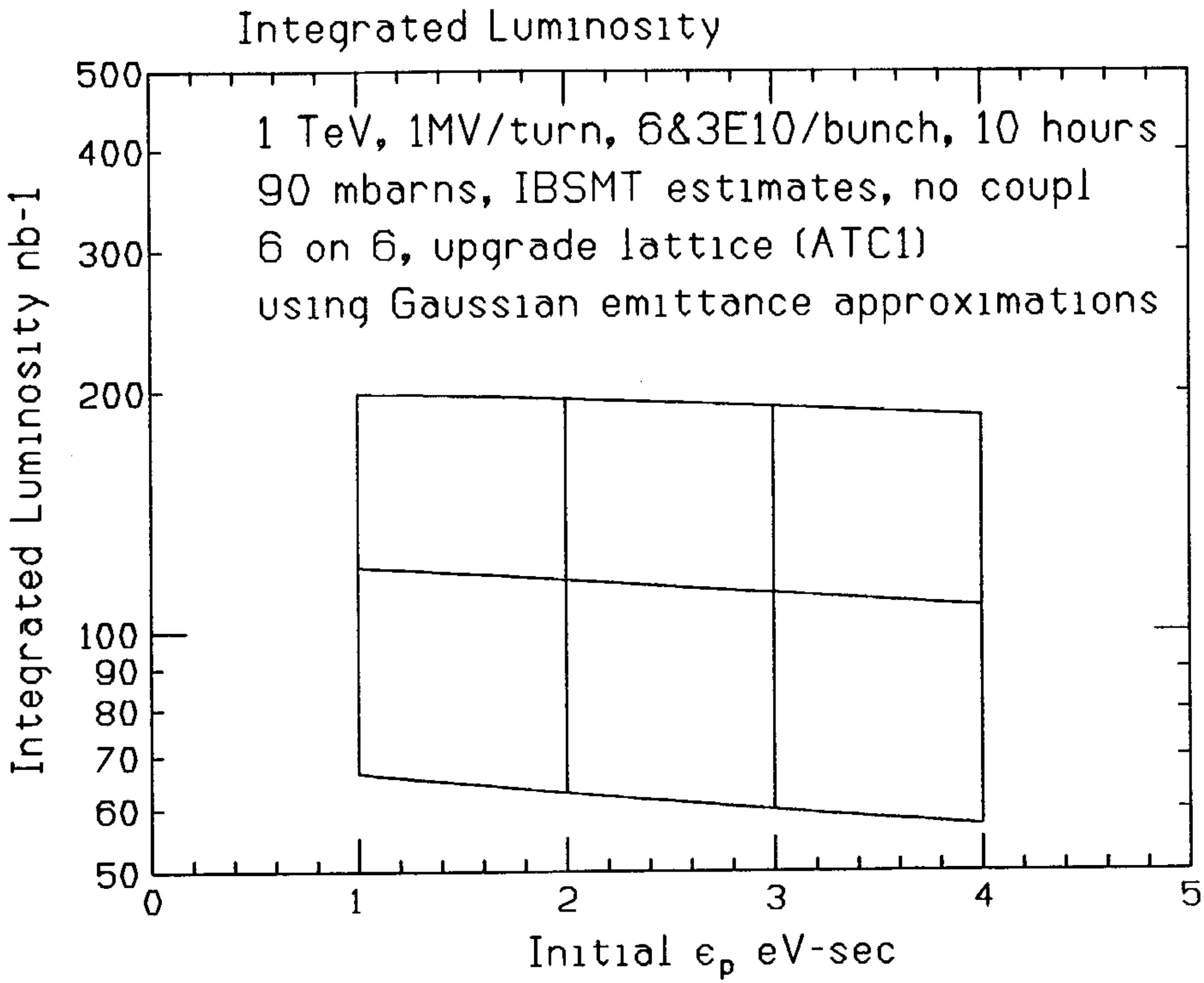
τ_{est} compared to τ_{IBSMT}
× 6 π mm-mrad
◇ 12 π mm-mrad
□ 24 π mm-mrad
1 TeV, 1MV/turn, 6E10/bunch
using approximate g(b)
$\Delta\tau_p/\tau_{p,IBSMT}$ %
$\Delta\tau_p = \tau_{p,est} - \tau_{p,IBSMT}$
$2\tau_{p,est} = 0.206\ \epsilon_x^{1.23}\ \epsilon_p^{1.68}$ hours
$\Delta\tau_x/\tau_{x,IBSMT}$ %
$\Delta\tau_x = \tau_{x,est} - \tau_{x,IBSMT}$
$2\tau_{x,est} = 0.055\ \epsilon_x^{2.24}\ \epsilon_p^{0.68}$ hours
ϵ_p eV-sec

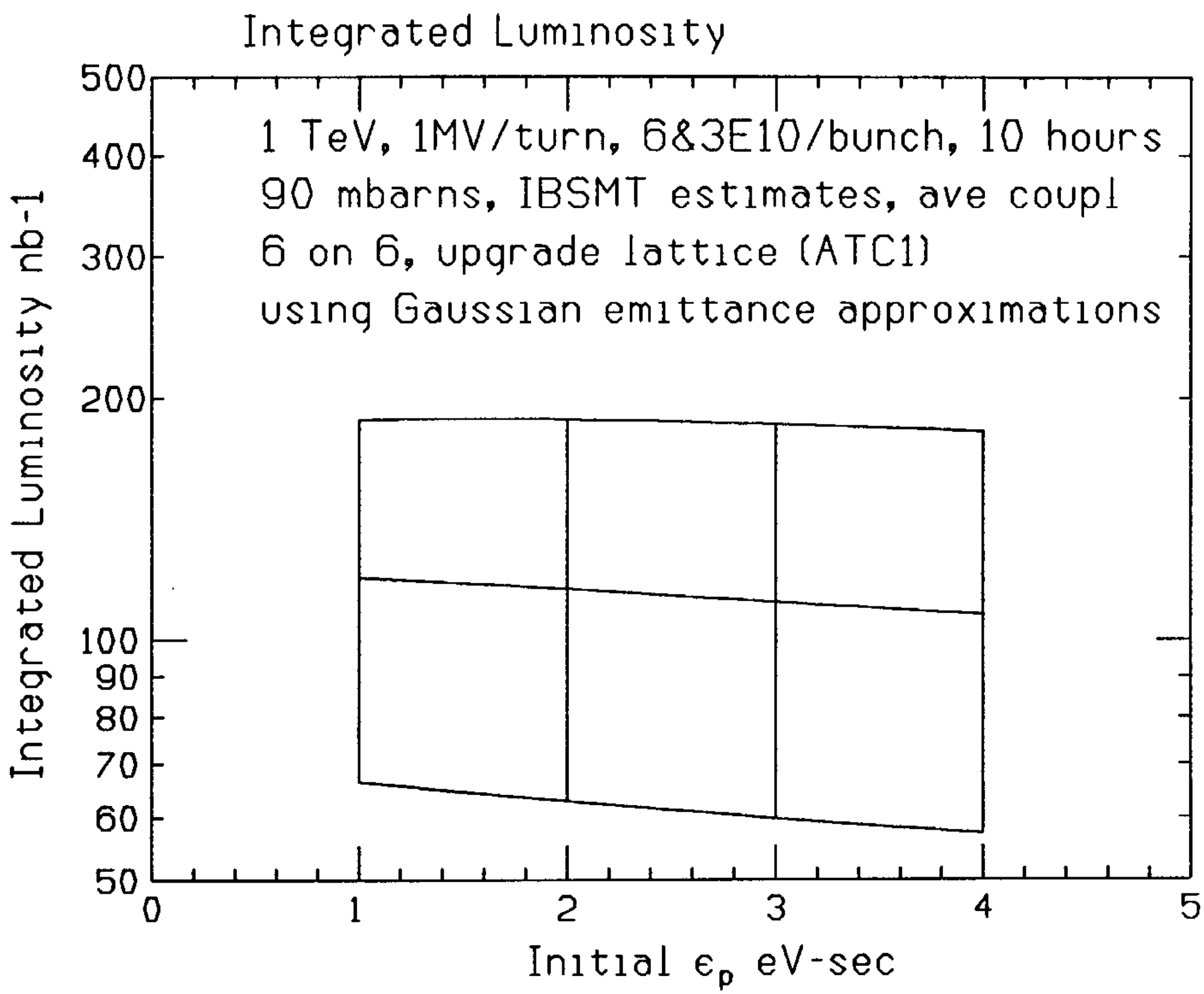
Figure 2a



τ_{est} compared to τ_{IBSMT}
× 6 π mm-mrad
◇ 12 π mm-mrad
□ 24 π mm-mrad
1 TeV, 1MV/turn, 6E10/bunch
using more exact g(b)
$\Delta\tau_p = \tau_{p,est} - \tau_{p,IBSMT}$
$2\tau_{p,est} = 0.187\ \epsilon_x^{1.24}\ \epsilon_p^{1.675}$ hours
$\Delta\tau_p/\tau_{p,IBSMT}$ %
$\Delta\tau_x = \tau_{x,est} - \tau_{x,IBSMT}$
$2\tau_{x,est} = 0.054\ \epsilon_x^{2.24}\ \epsilon_p^{0.675}$ hours
$\Delta\tau_x/\tau_{x,IBSMT}$ %
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
ϵ_p eV-sec

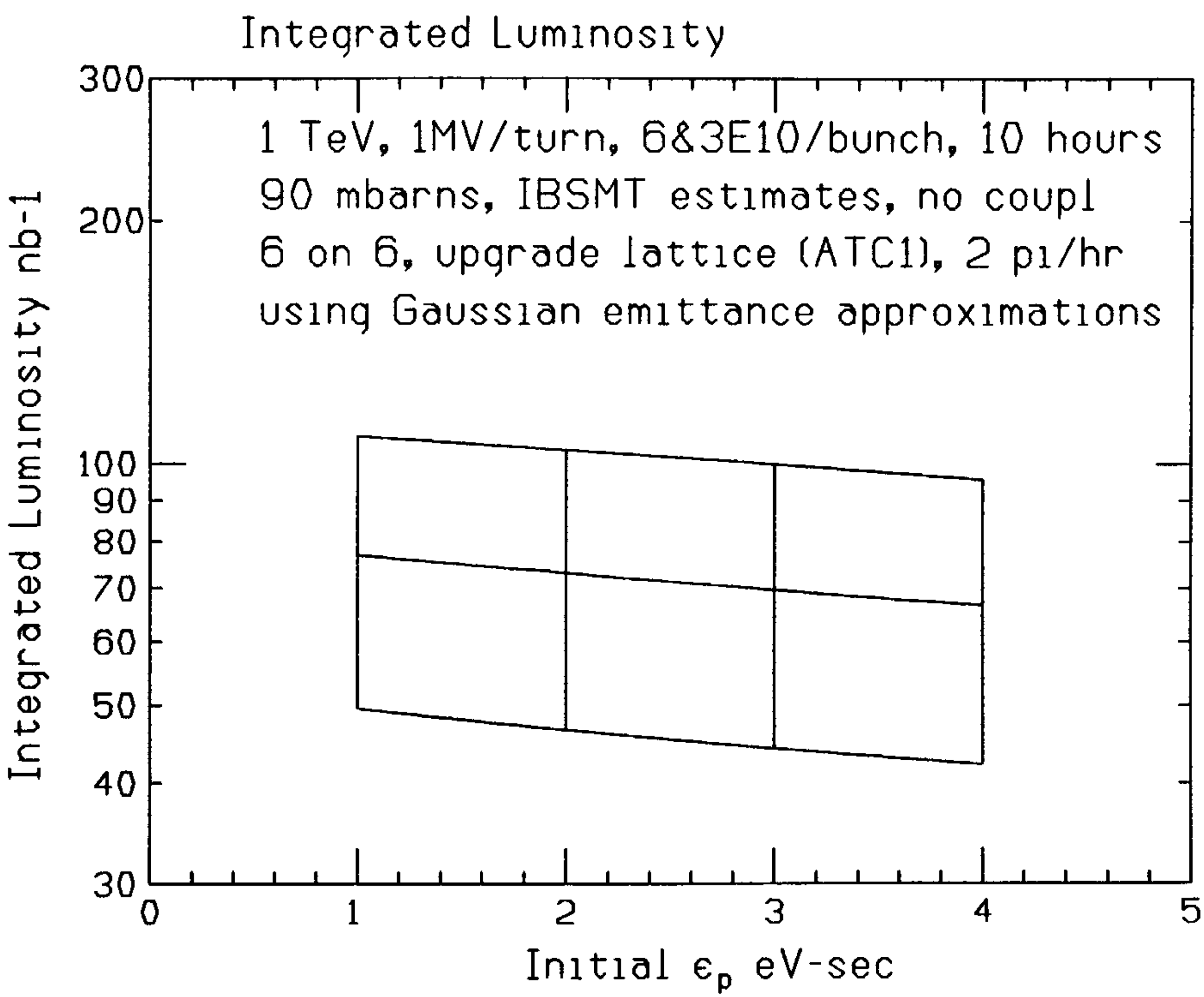
Figure 2b


Integrated Luminosity
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
Integrated Luminosity nb-1
500
400
300
200
100
90
80
70
60
50
0
1
2
3
4
5
Initial ϵ_p eV-sec
Figure 3a



Integrated Luminosity
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
500
400
300
200
100
90
80
70
60
50
Integrated Luminosity nb-1
0
1
2
3
4
5
Initial ϵ_p eV-sec

Figure 3b


Integrated Luminosity
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1), 2 pi/hr
using Gaussian emittance approximations
Integrated Luminosity nb-1
300
200
100
90
80
70
60
50
40
30
0
1
2
3
4
5
Initial ϵ_p eV-sec
Figure 3c

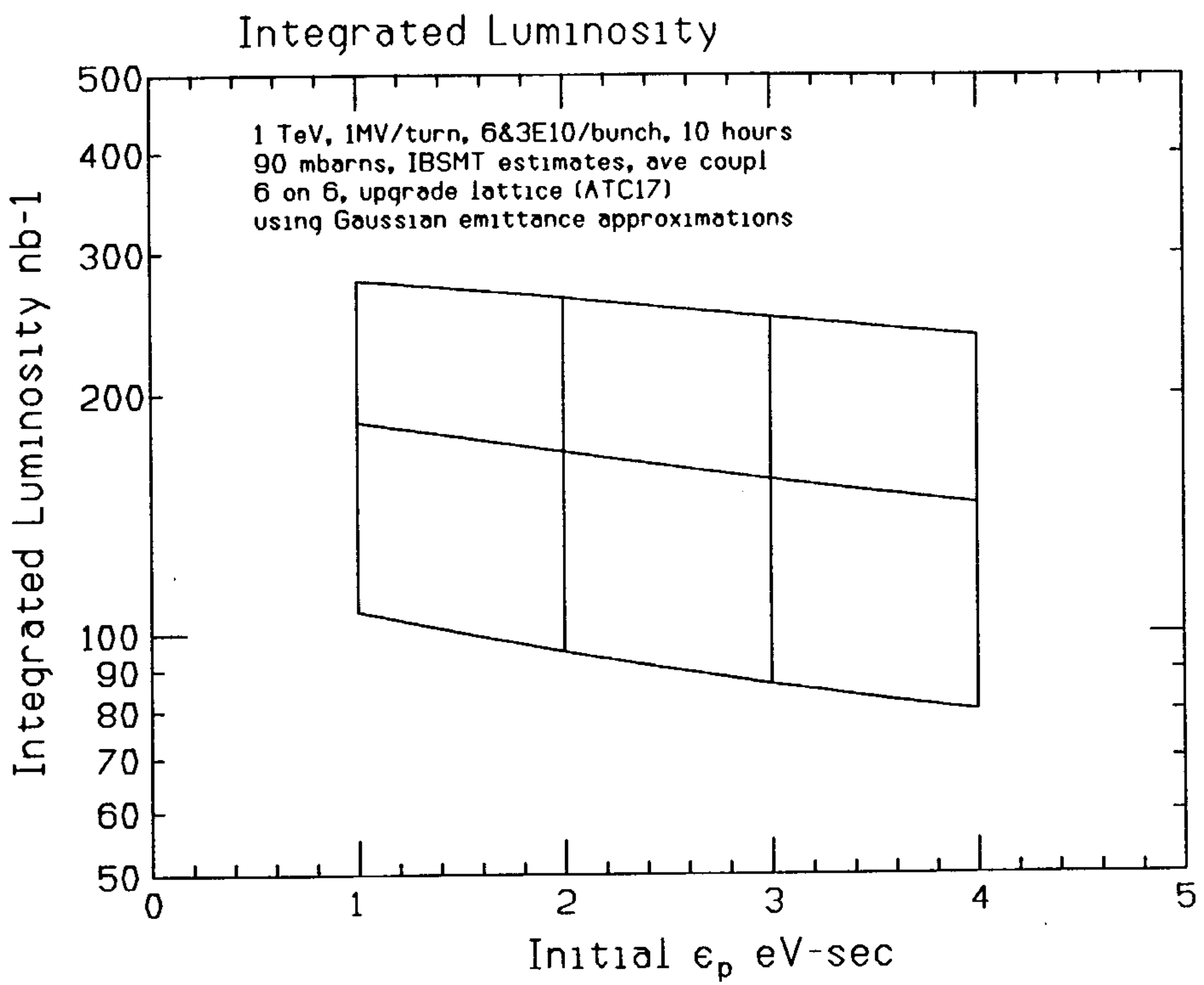

Integrated Luminosity
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC17)
using Gaussian emittance approximations
Integrated Luminosity nb-1
500
400
300
200
100
90
80
70
60
50
0
1
2
3
4
5
Initial ϵ_p eV-sec

Figure 3d

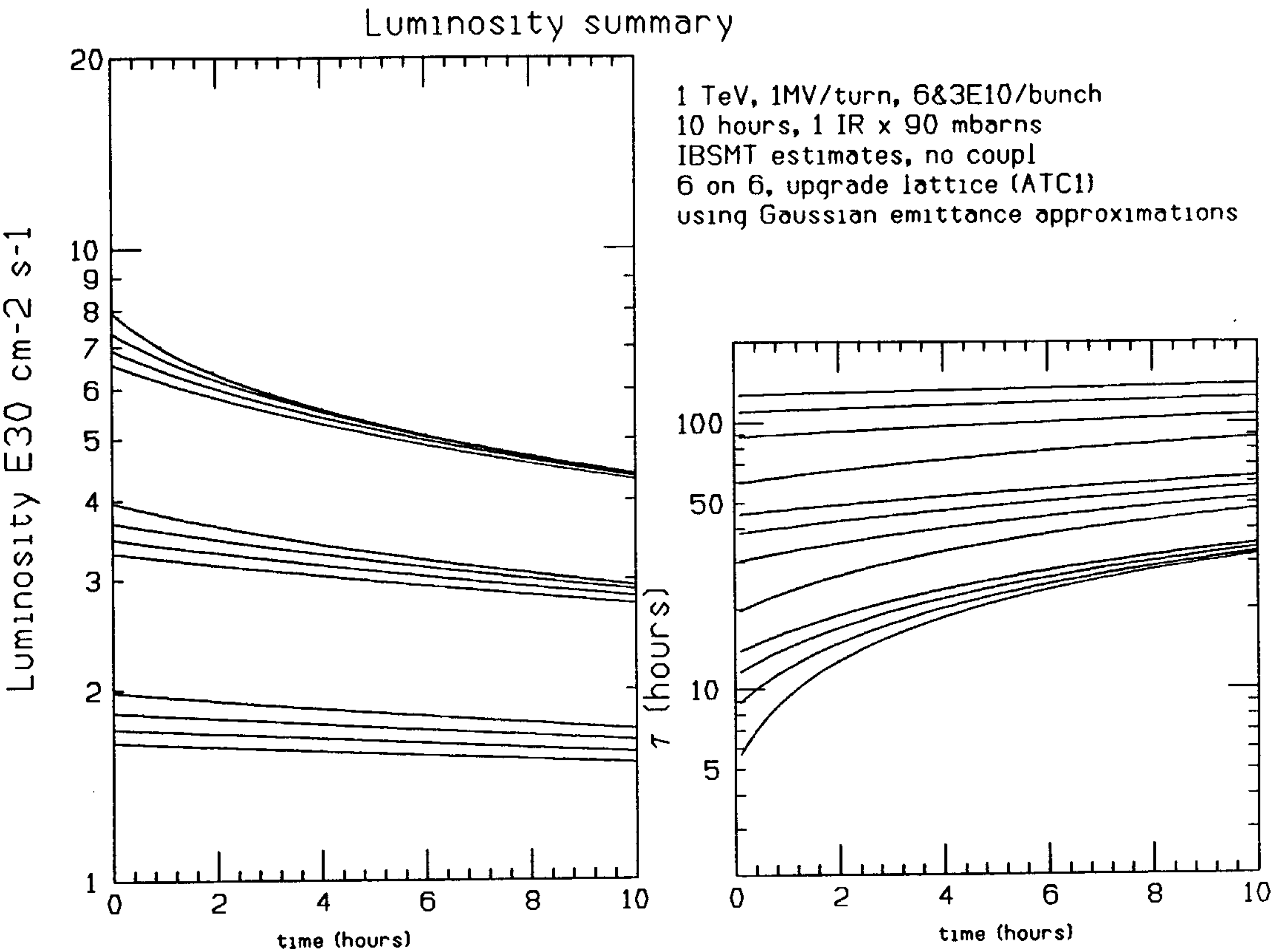
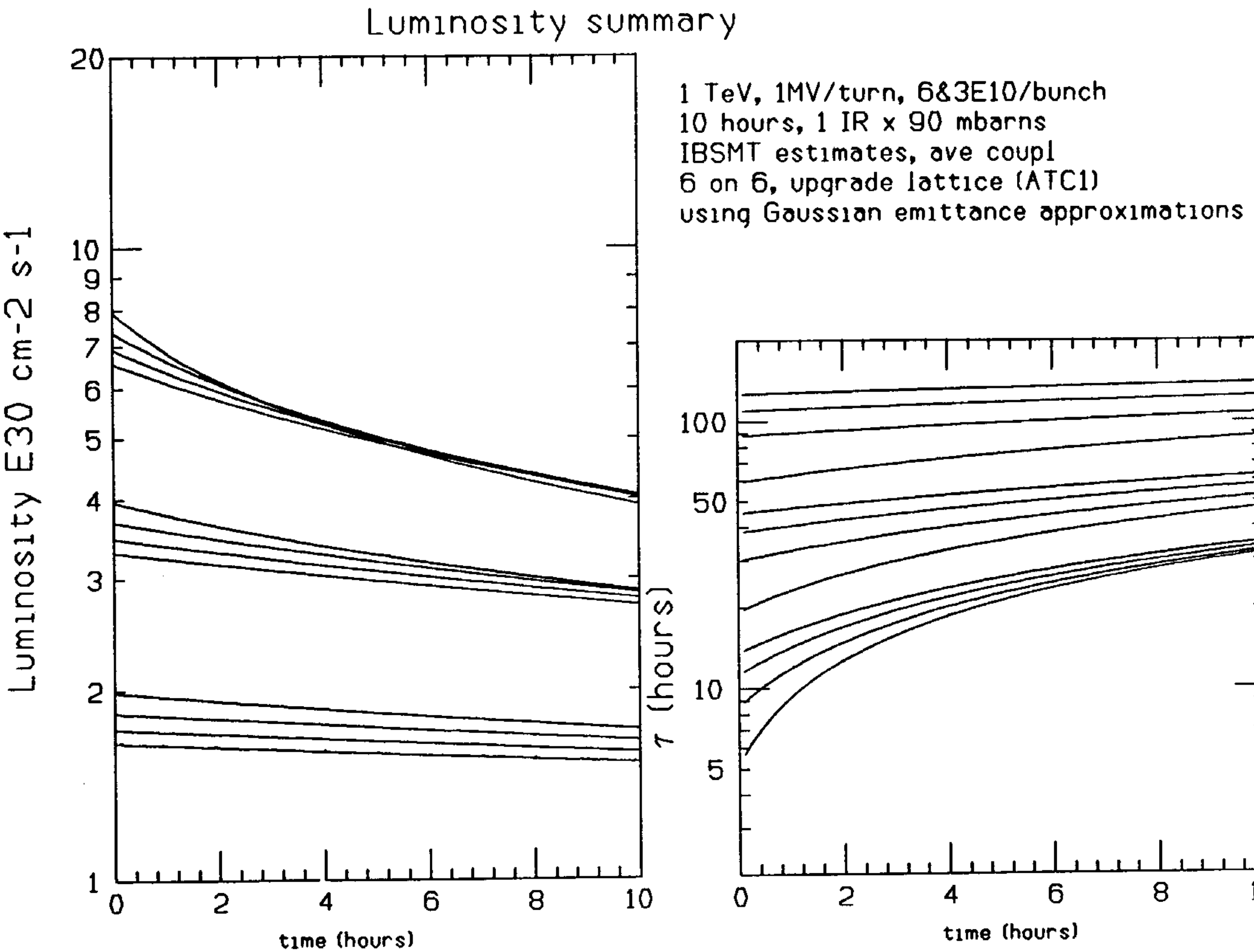

Luminosity summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
Luminosity E30 cm-2 s-1
time (hours)
τ (hours)
time (hours)

Figure 4a



Luminosity summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
Luminosity E30 cm-2 s-1
20
10
9
8
7
6
5
4
3
2
1
0
2
4
6
8
10
time (hours)
τ (hours)
100
50
10
5
0
2
4
6
8
10
time (hours)

Figure 4b

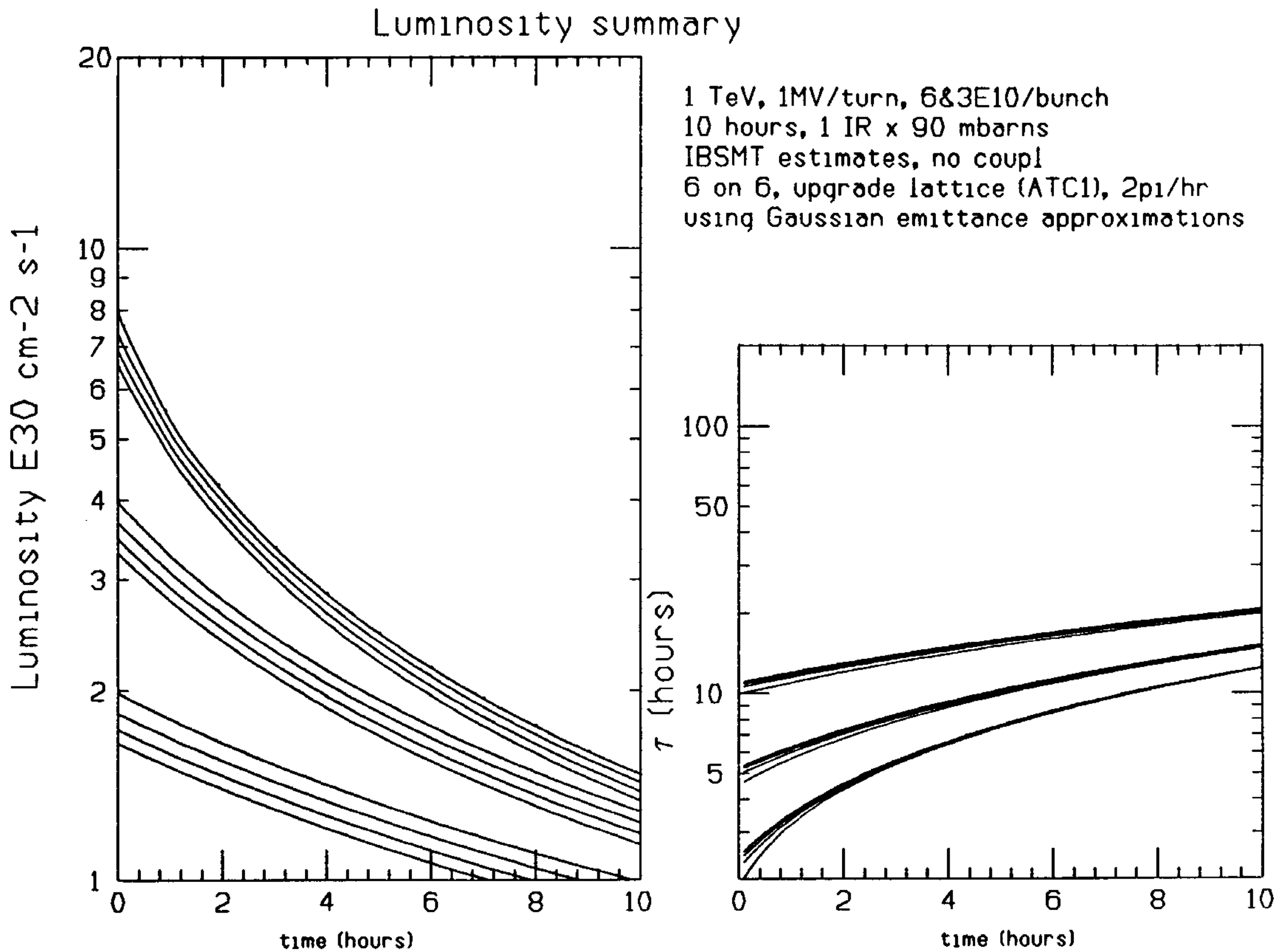

Luminosity summary
Luminosity E30 cm-2 s-1
20
10
9
8
7
6
5
4
3
2
1
0
2
4
6
8
10
time (hours)
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1), 2pi/hr
using Gaussian emittance approximations
τ (hours)
100
50
10
5
0
2
4
6
8
10
time (hours)

Figure 4c

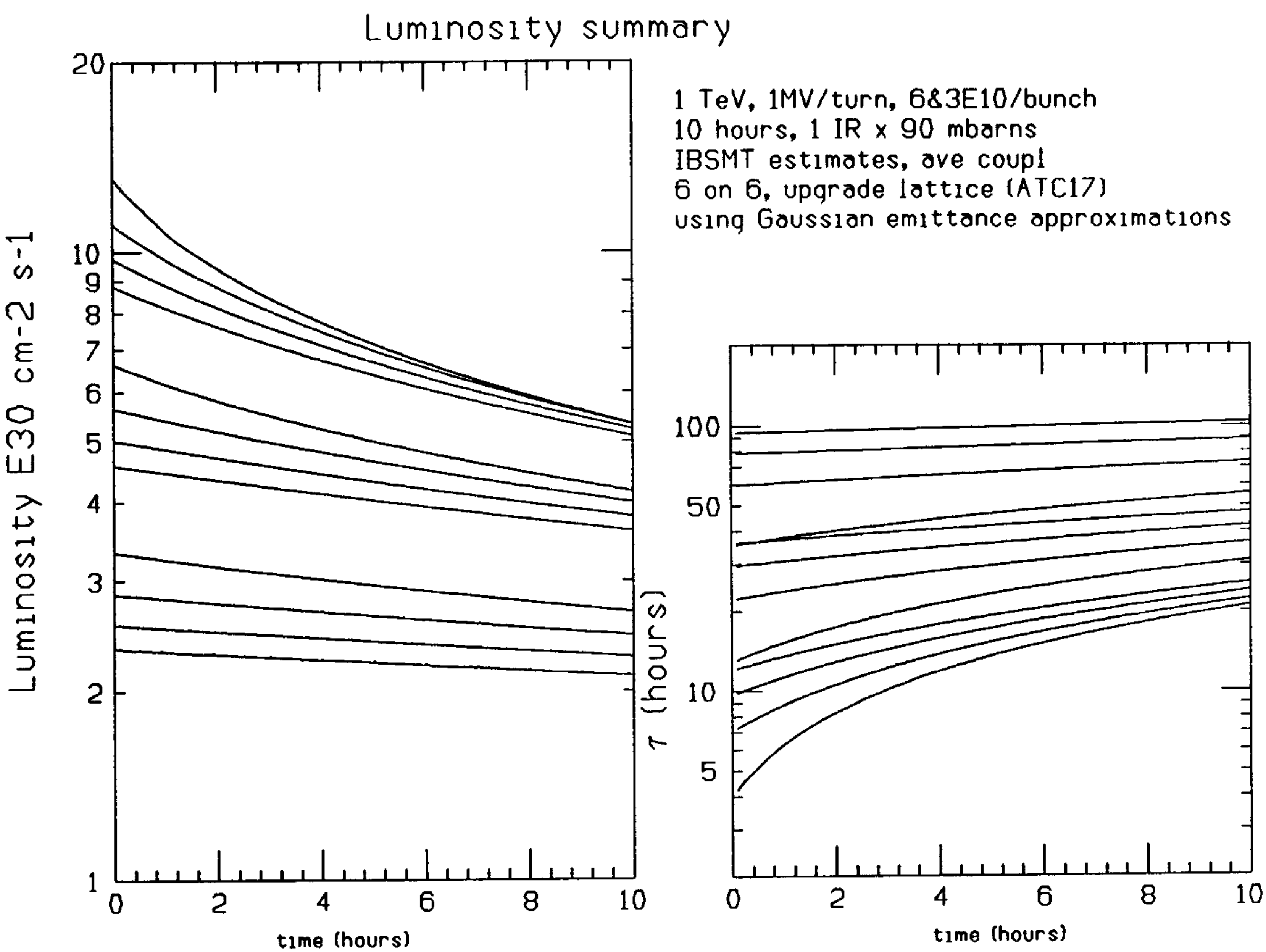
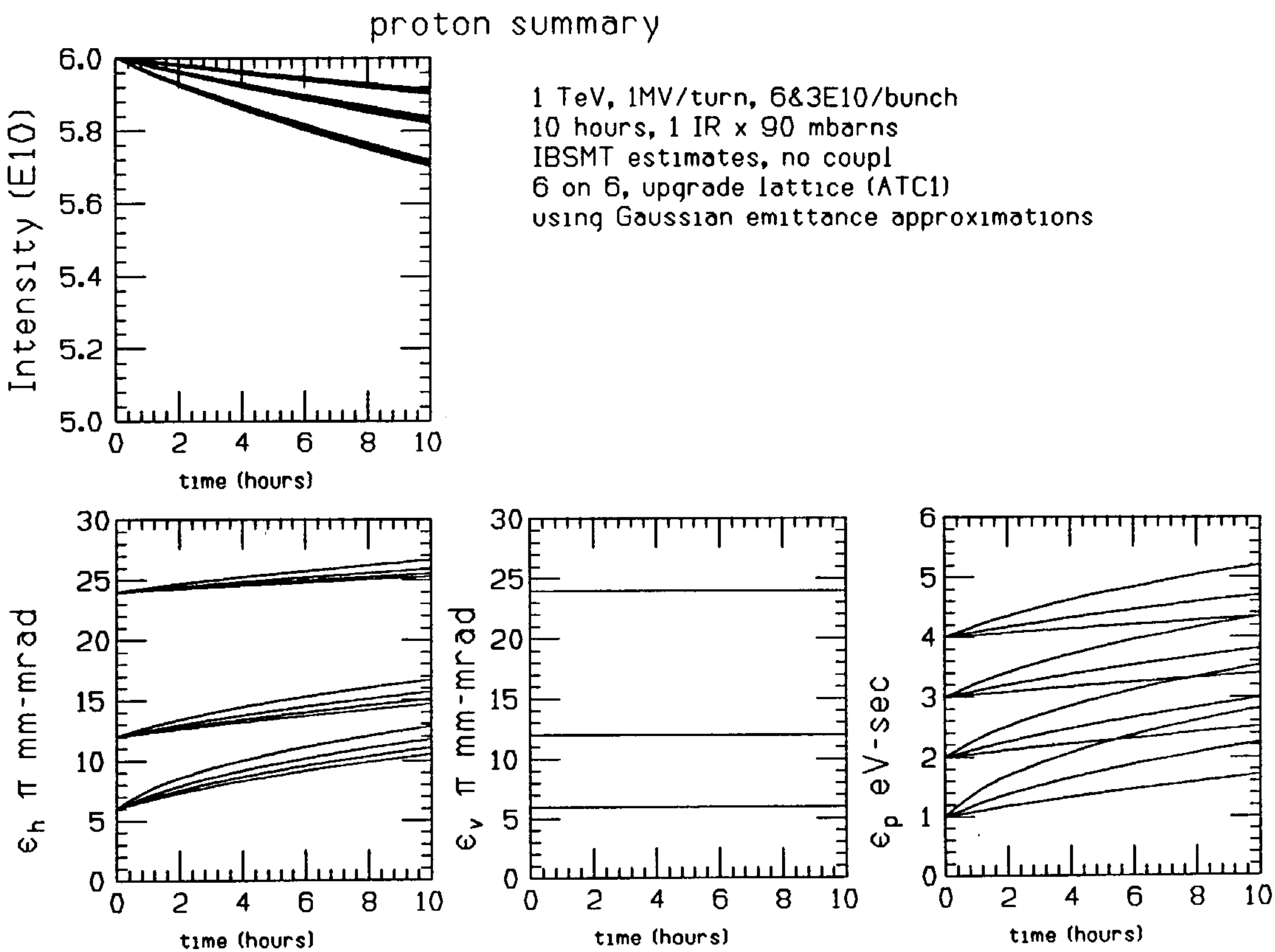

Luminosity summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC17)
using Gaussian emittance approximations
Luminosity E30 cm-2 s-1
20
10
9
8
7
6
5
4
3
2
1
0
2
4
6
8
10
time (hours)
τ (hours)
100
50
10
5
0
2
4
6
8
10
time (hours)

Figure 4d



proton summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
Intensity (E10)
6.0
5.8
5.6
5.4
5.2
5.0
0
2
4
6
8
10
time (hours)
ϵ_h π mm-mrad
ϵ_v π mm-mrad
ϵ_p eV-sec
30
25
20
15
10
5

Figure 5a

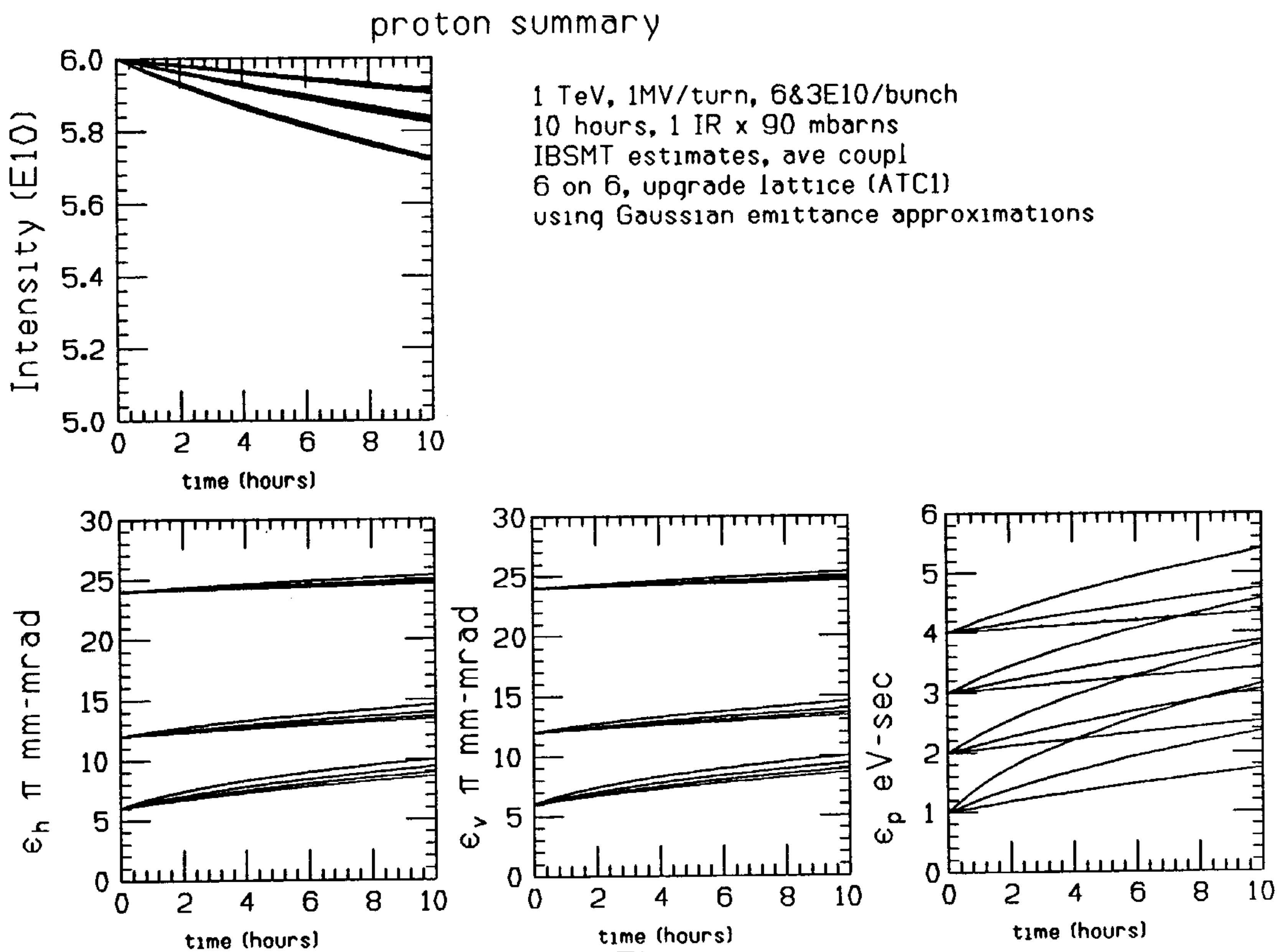

proton summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
Intensity (E10)
6.0
5.8
5.6
5.4
5.2
5.0
0
2
4
6
8
10
time (hours)
ε_h π mm-mrad
ε_v π mm-mrad
ε_p eV-sec
30
25
20
15
10
5
0
6
5
4
3
2
1
time (hours)

Figure 5b

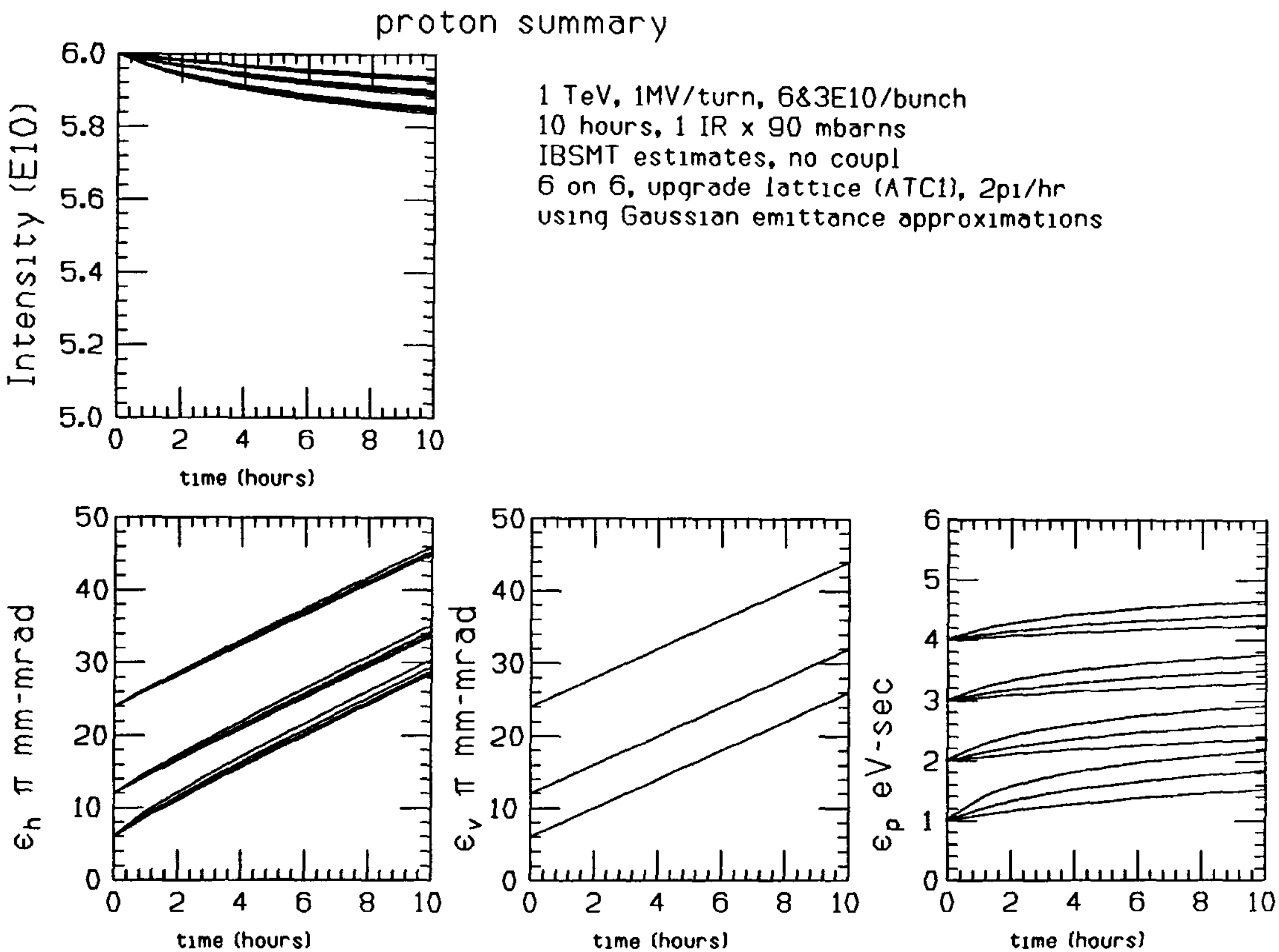
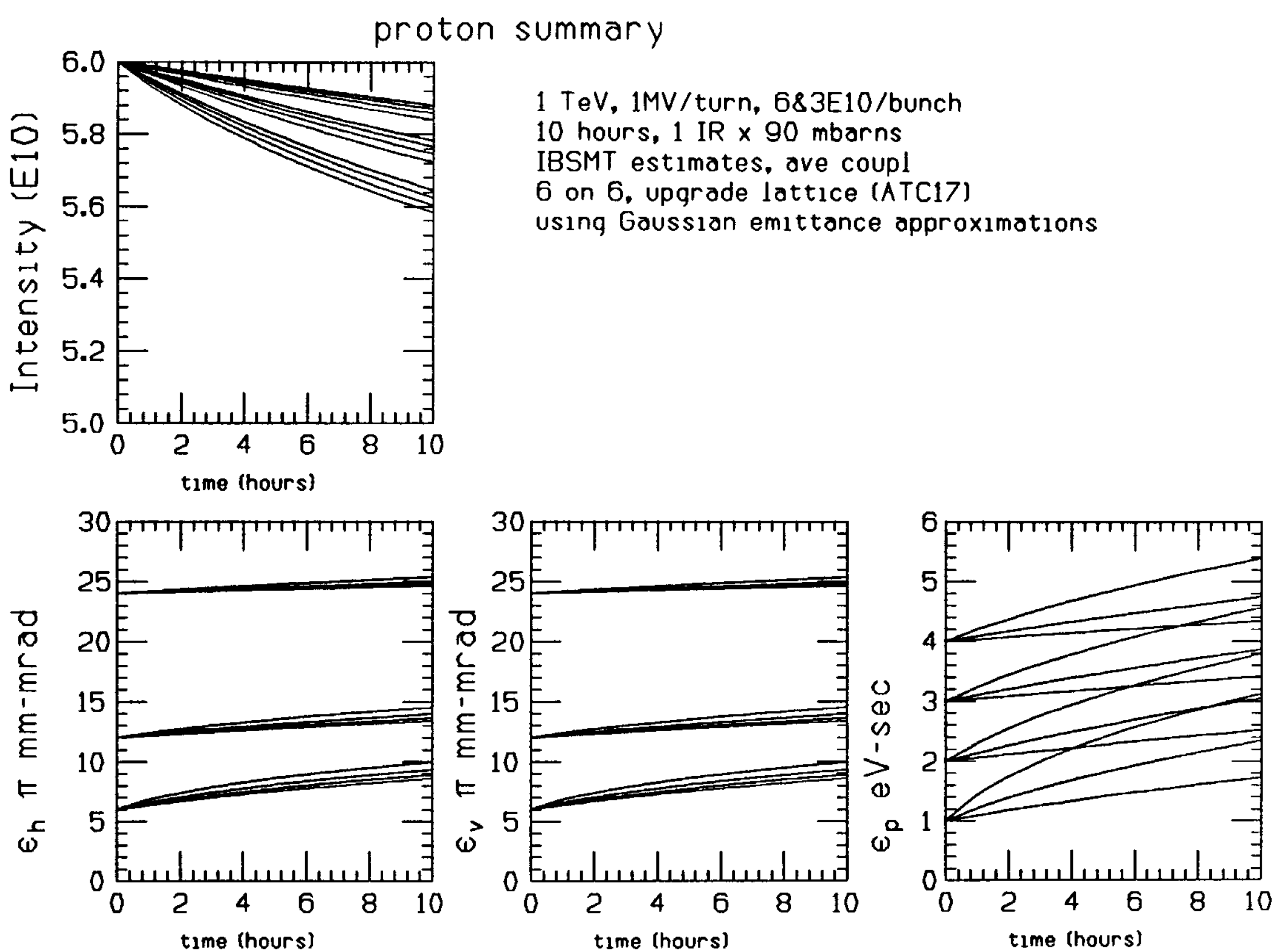
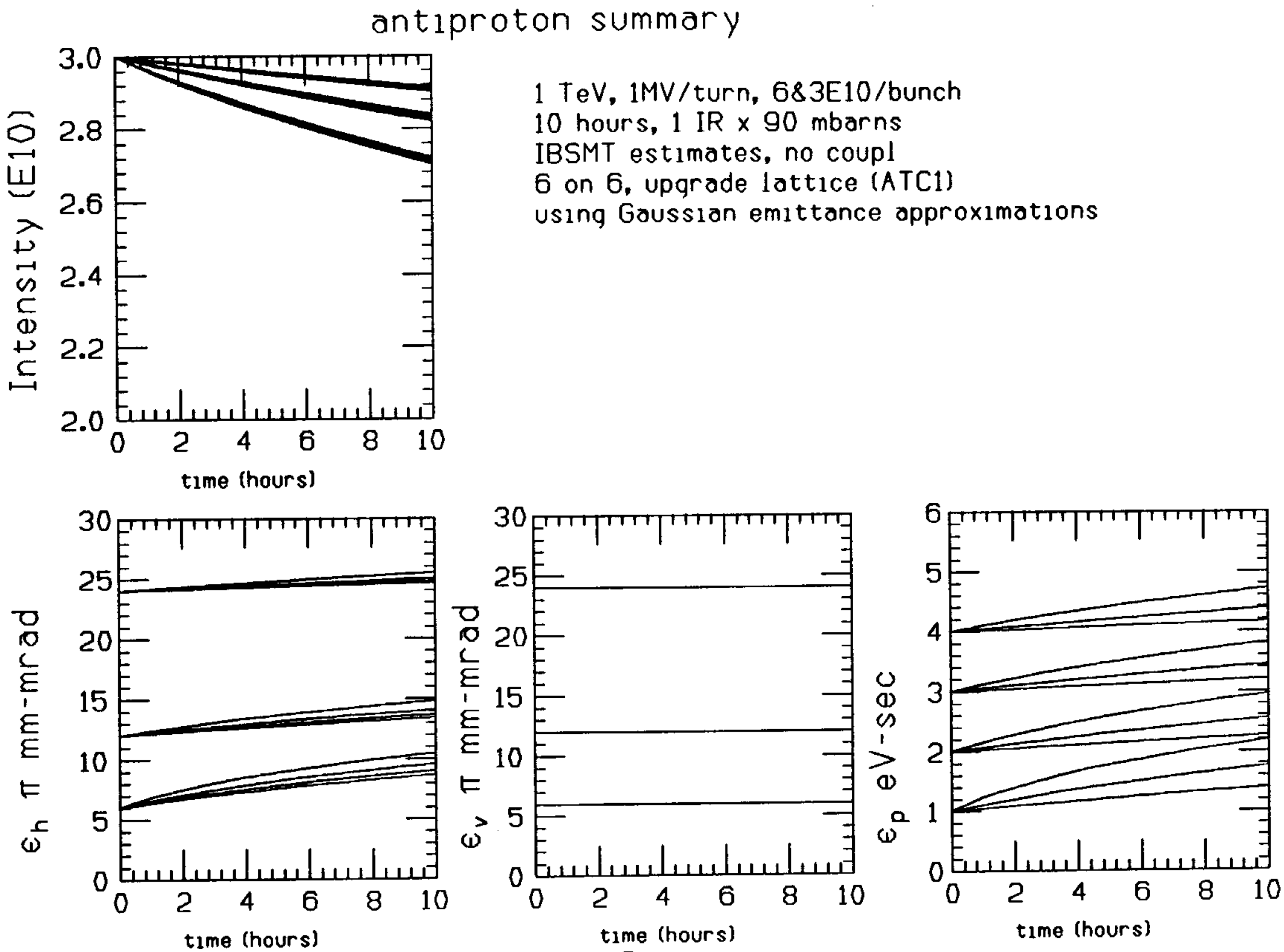

proton summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1), 2pi/hr
using Gaussian emittance approximations
Intensity (E10)
6.0
5.8
5.6
5.4
5.2
5.0
0
2
4
6
8
10
time (hours)
ϵ_h π mm-mrad
ϵ_v π mm-mrad
ϵ_p eV-sec
50
40
30
20
10
0
6
5
4
3
2
1
time (hours)
time (hours)
time (hours)

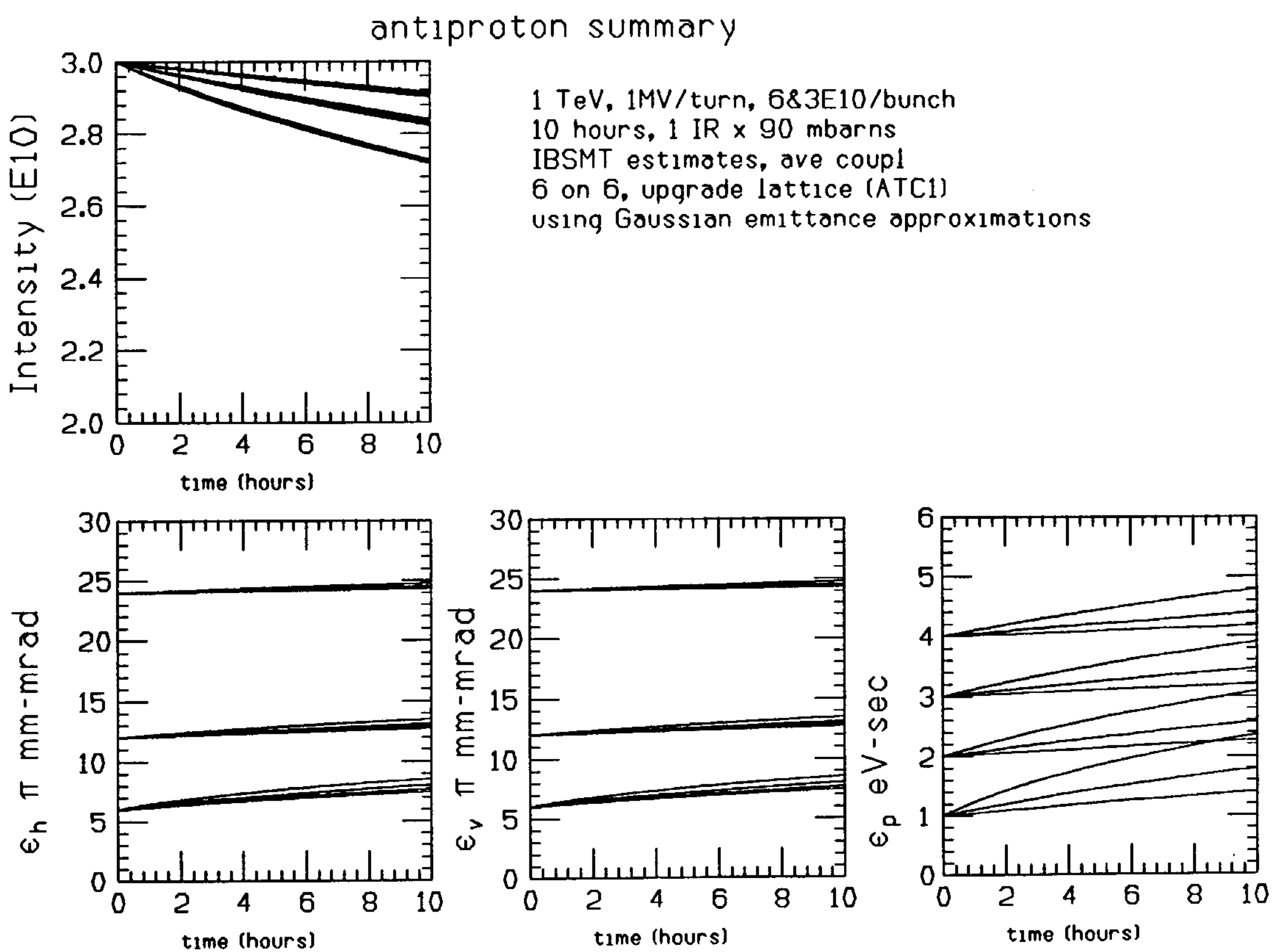
Figure 5c



proton summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC17)
using Gaussian emittance approximations
Intensity (E10)
6.0
5.8
5.6
5.4
5.2
5.0
0
2
4
6
8
10
time (hours)
ϵ_h π mm-mrad
ϵ_v π mm-mrad
ϵ_p eV-sec
30
25
20
15
10
5
0

Figure 5d


antiproton summary
Intensity (E10)
3.0
2.8
2.6
2.4
2.2
2.0
0
2
4
6
8
10
time (hours)
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
ϵ_h π mm-mrad
30
25
20
15
10
5
0
time (hours)
ϵ_v π mm-mrad
time (hours)
ϵ_p eV-sec
6
5
4
3
2
1
0
time (hours)
Figure 6a



antiproton summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
Intensity (E10)
time (hours)
ε_h π mm-mrad
ε_v π mm-mrad
ε_p eV-sec

Figure 6b

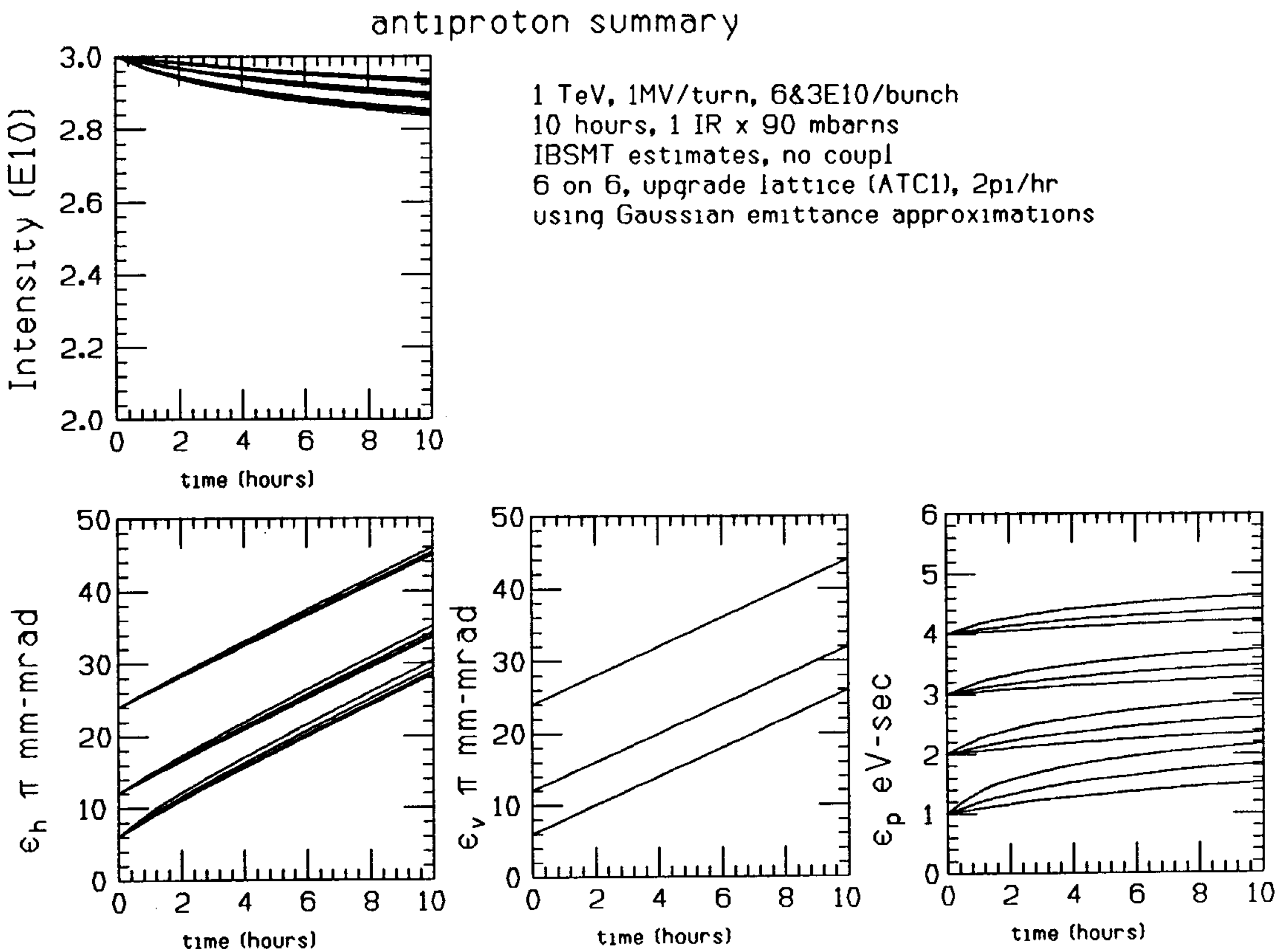

antiproton summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1), 2pi/hr
using Gaussian emittance approximations
Intensity (E10)
3.0
2.8
2.6
2.4
2.2
2.0
time (hours)
ϵ_h π mm-mrad
ϵ_v π mm-mrad
ϵ_p eV-sec
0
2
4
6
8
10
20
30
40
50
1
3
5

Figure 6c

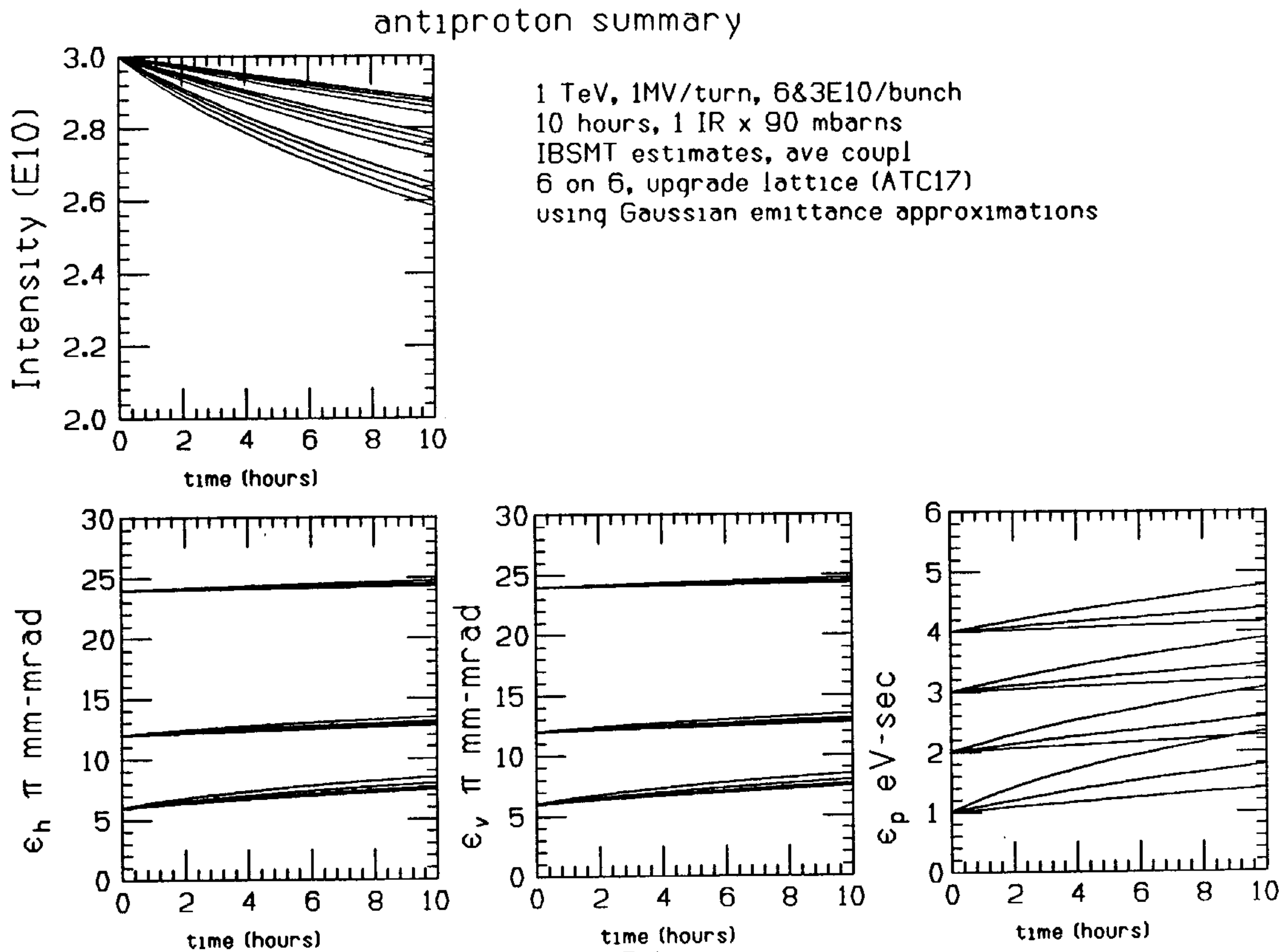
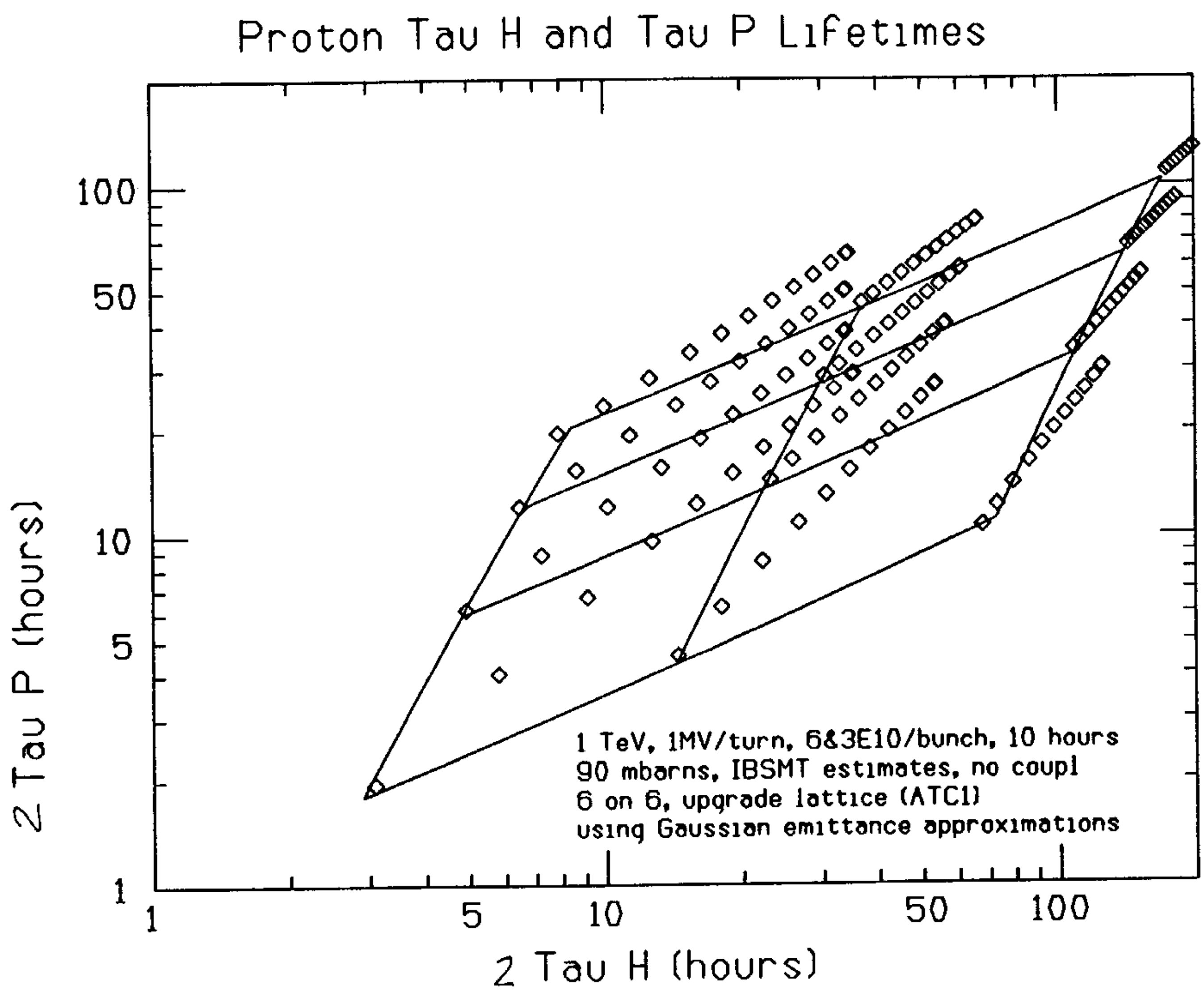

antiproton summary
1 TeV, 1MV/turn, 6&3E10/bunch
10 hours, 1 IR x 90 mbarns
IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC17)
using Gaussian emittance approximations
Intensity (E10)
3.0
2.8
2.6
2.4
2.2
2.0
0
2
4
6
8
10
time (hours)
ϵ_h π mm-mrad
ϵ_v π mm-mrad
ϵ_p eV-sec
30
25
20
15
10
5
6
5
4
3
2
1

Figure 6d



Proton Tau H and Tau P Lifetimes
2 Tau P (hours)
2 Tau H (hours)
1
5
10
50
100
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations

Figure 7a

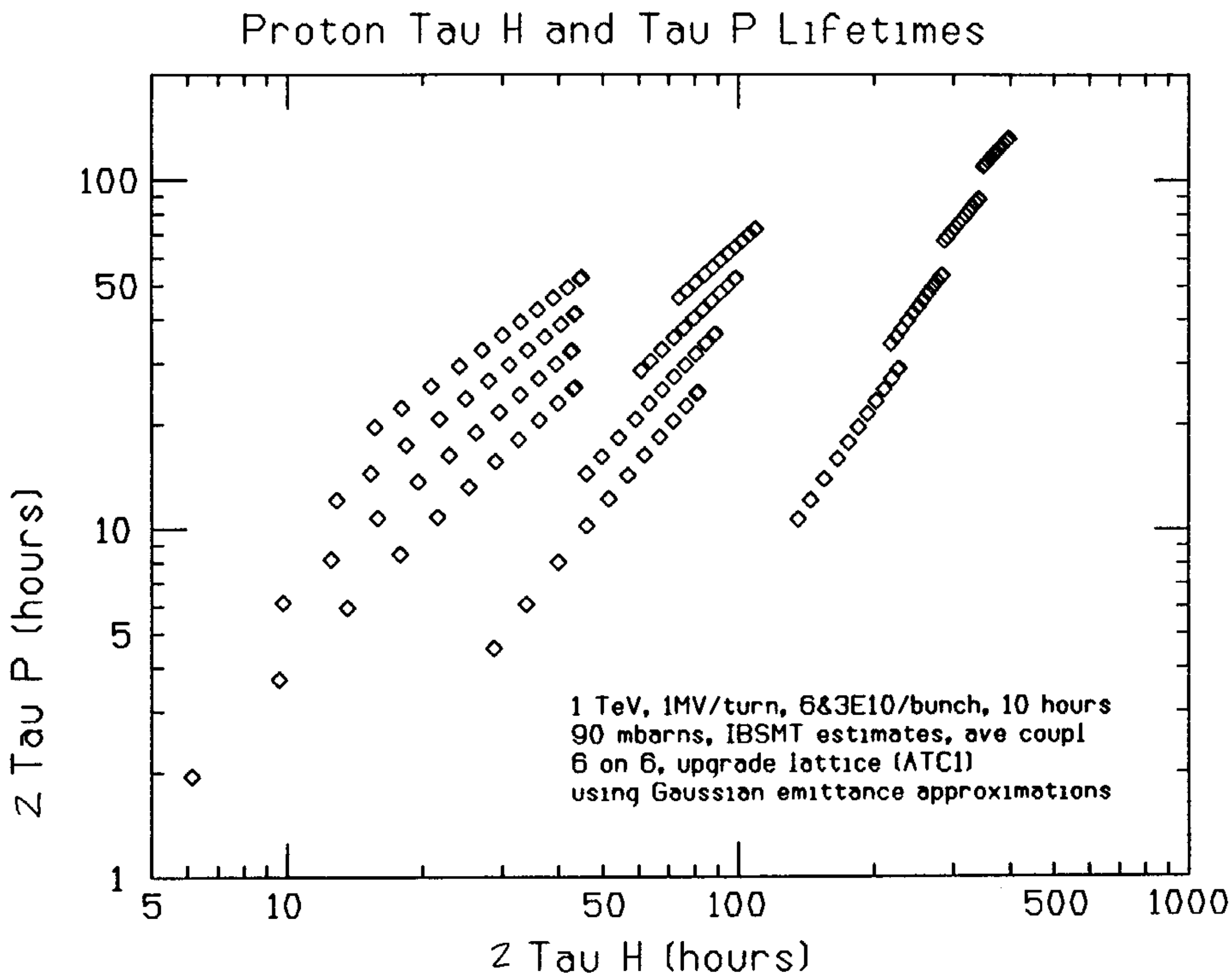
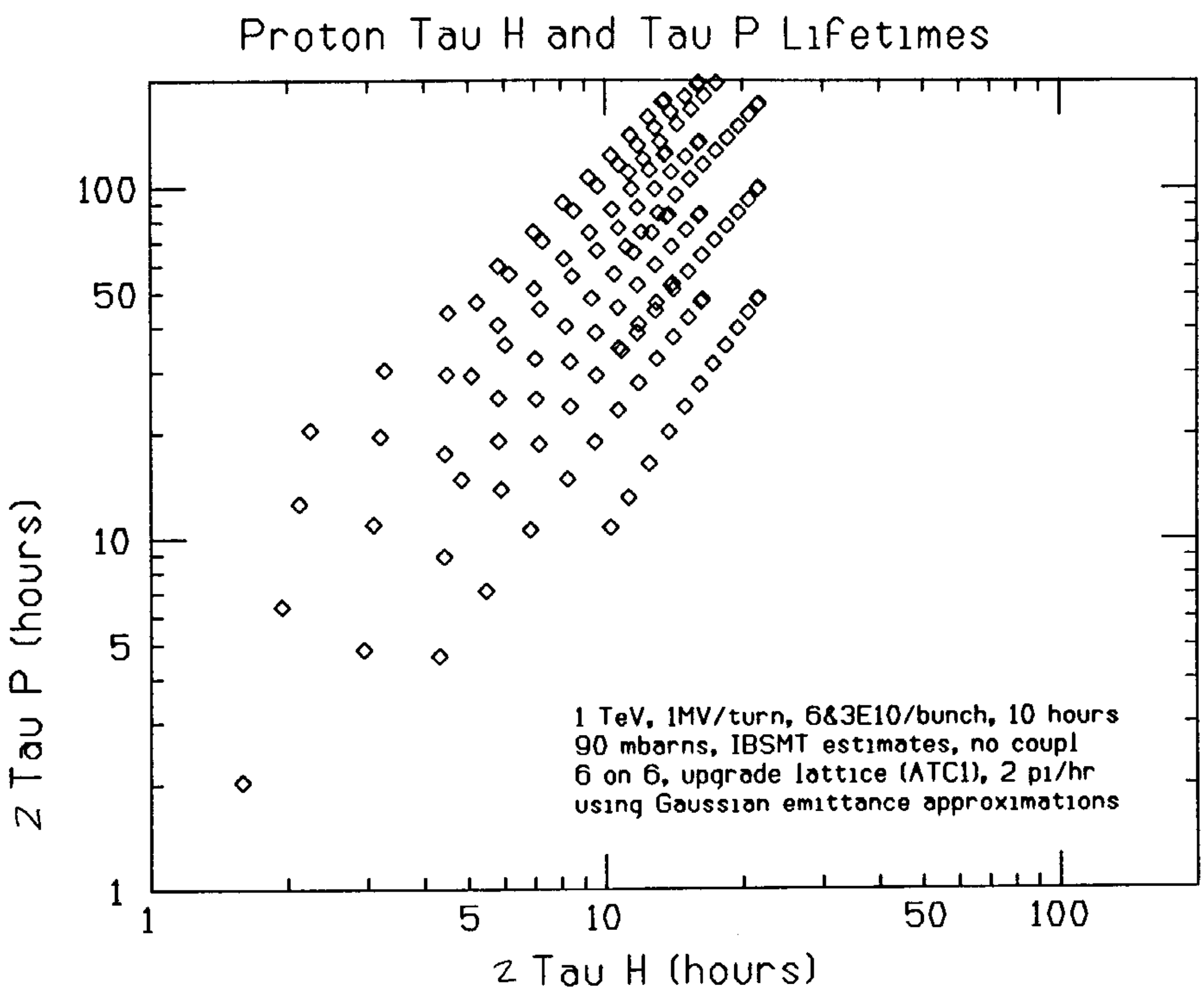

Proton Tau H and Tau P Lifetimes
2 Tau P (hours)
2 Tau H (hours)
1
5
10
50
100
500
1000
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations

Figure 7b



Proton Tau H and Tau P Lifetimes
100
50
10
5
1
1
5
10
50
100
2 Tau P (hours)
2 Tau H (hours)
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1), 2 pi/hr
using Gaussian emittance approximations

Figure 7c

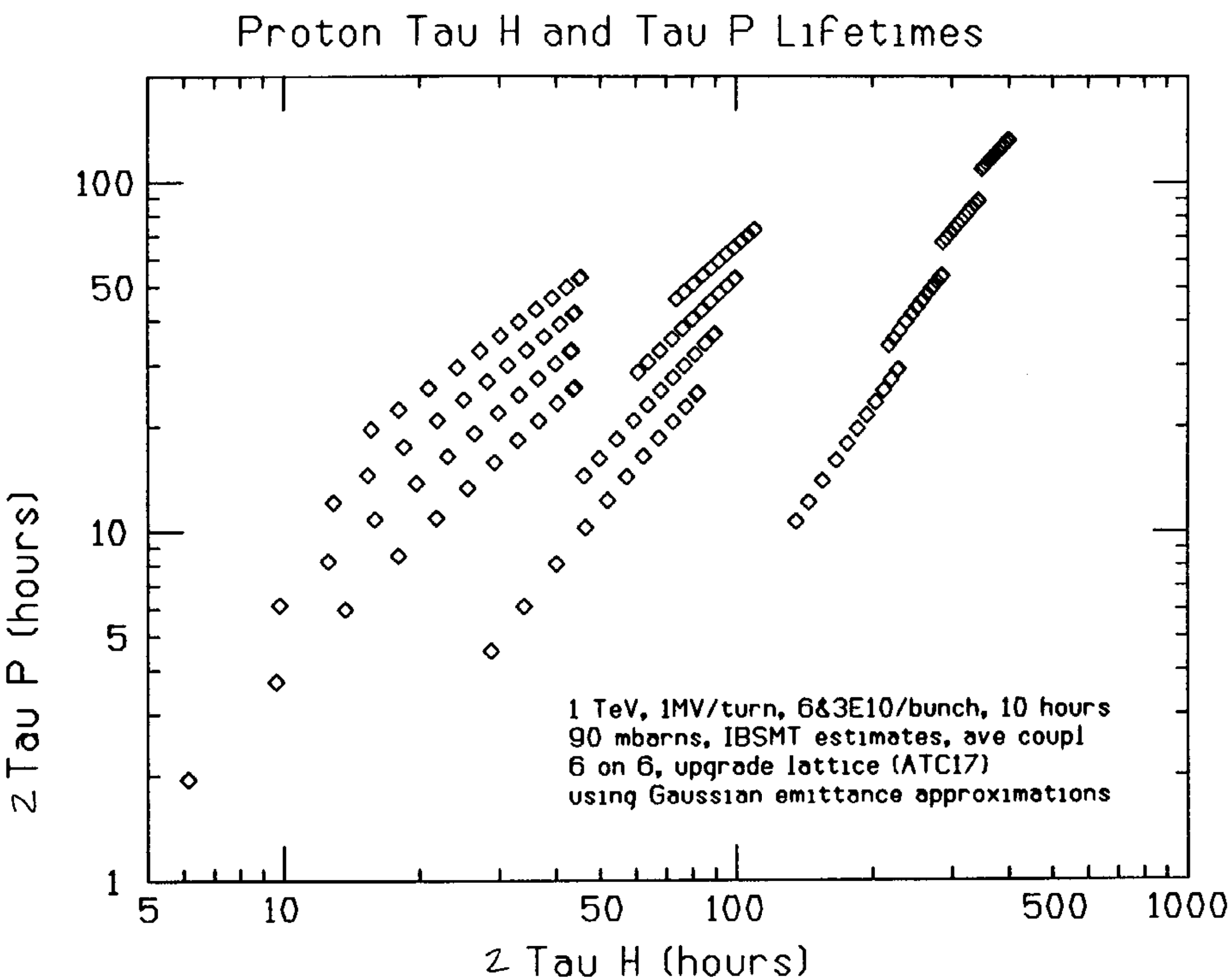

Proton Tau H and Tau P Lifetimes
2 Tau P (hours)
100
50
10
5
1
5
10
50
100
500
1000
2 Tau H (hours)
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC17)
using Gaussian emittance approximations

Figure 7d

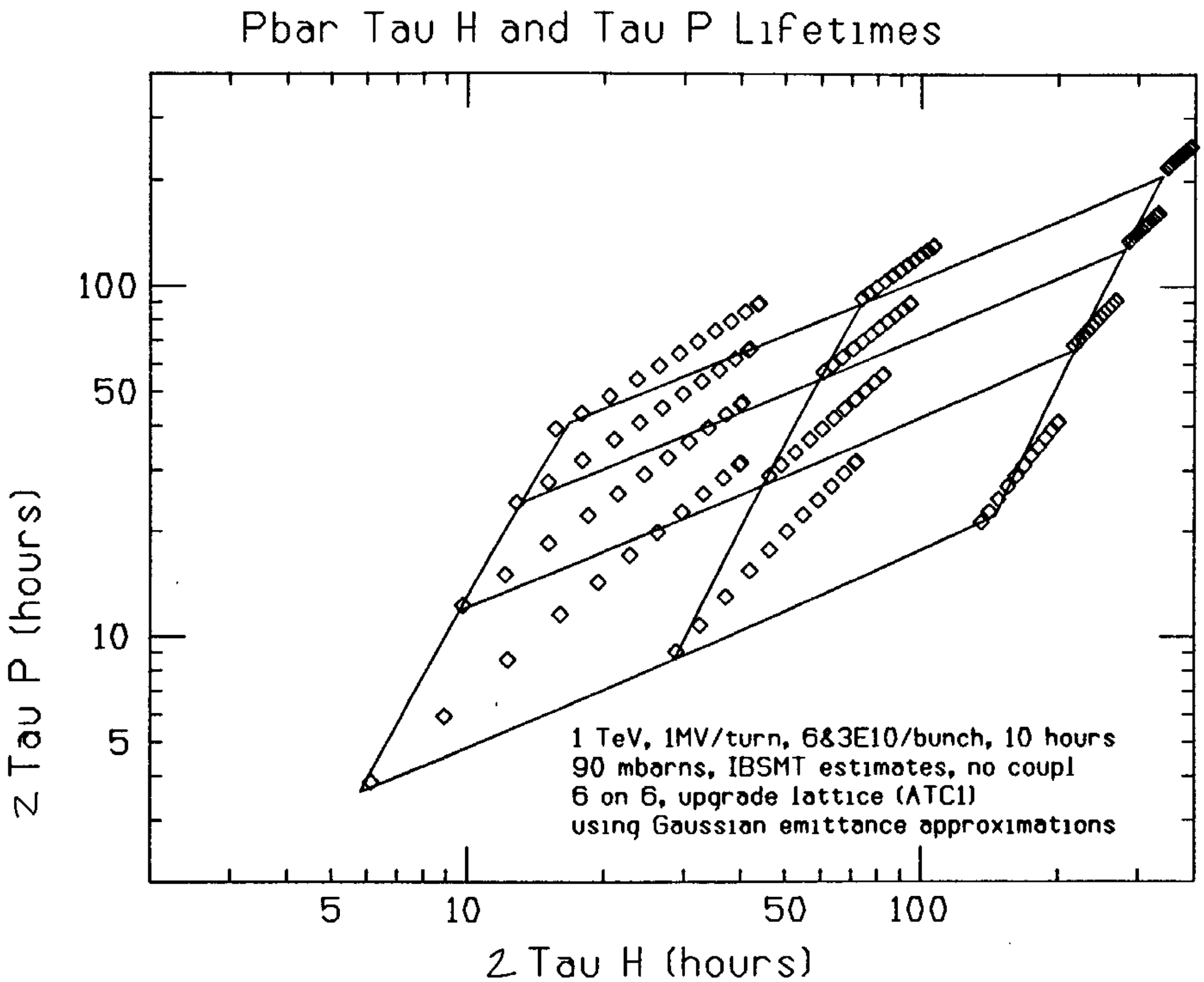

Pbar Tau H and Tau P Lifetimes
100
50
10
5
2 Tau P (hours)
5
10
50
100
2 Tau H (hours)
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations

Figure 8a

Pbar Tau H and Tau P Lifetimes

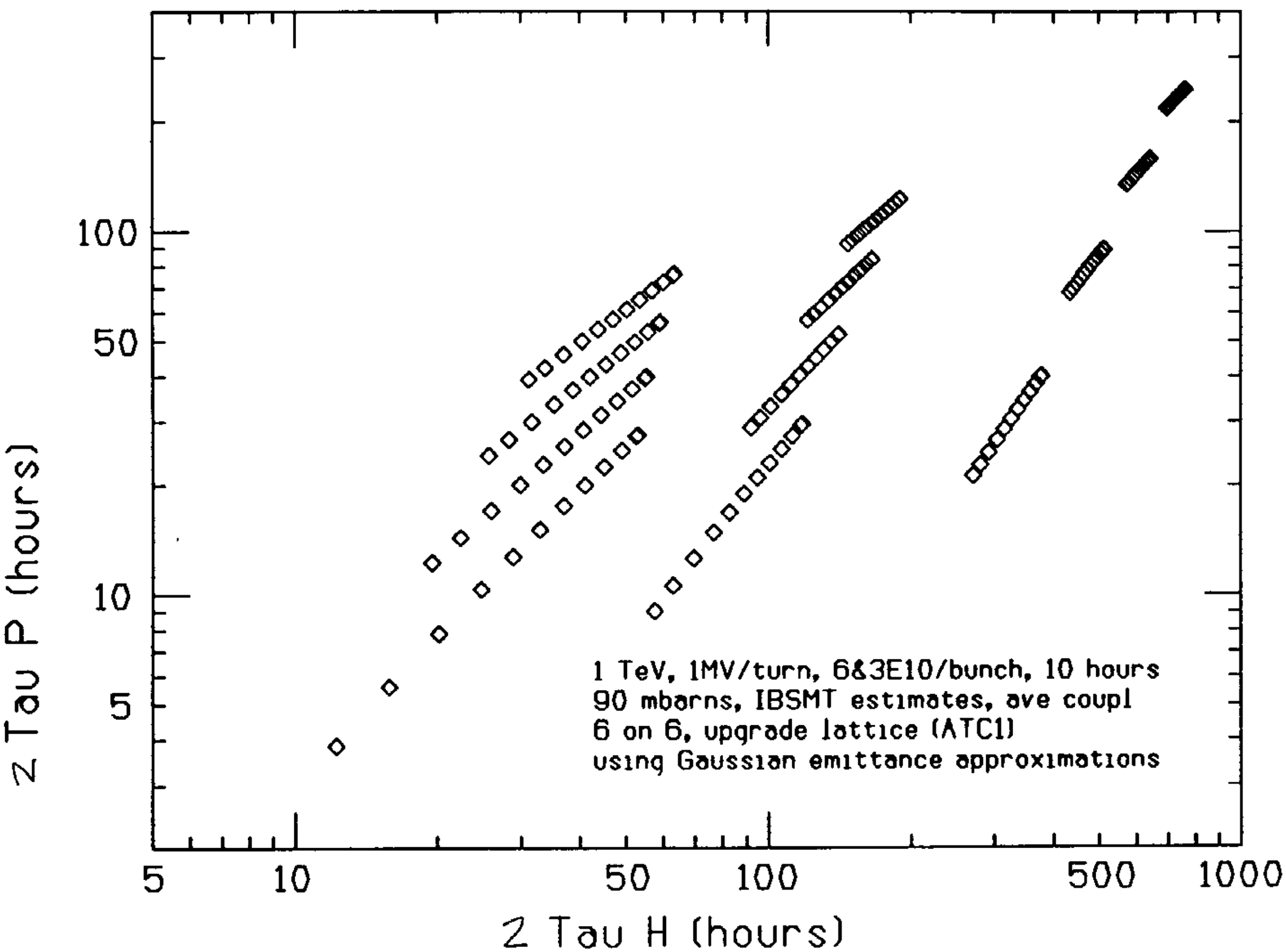


Figure 8b

Pbar Tau H and Tau P Lifetimes

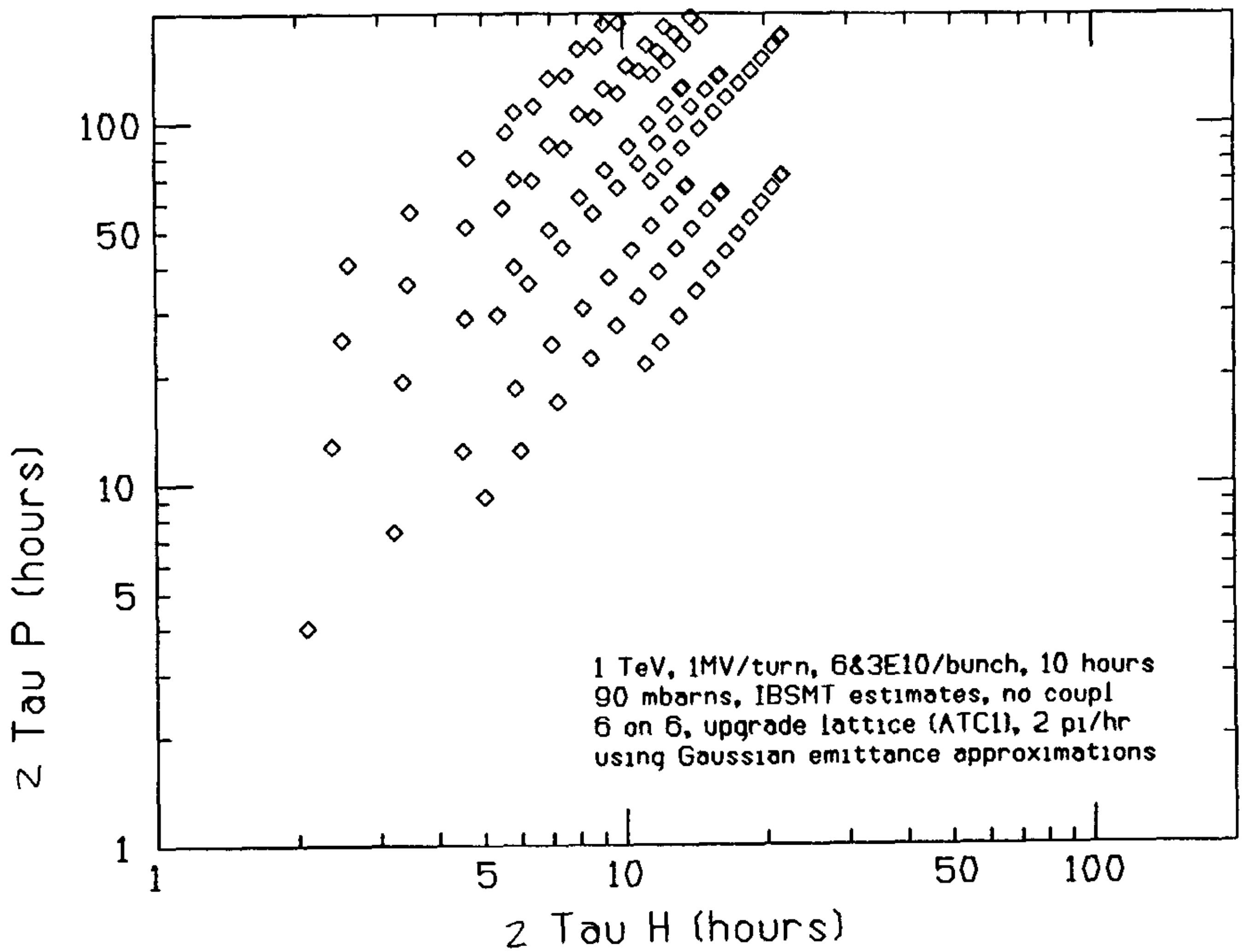


Figure 8c

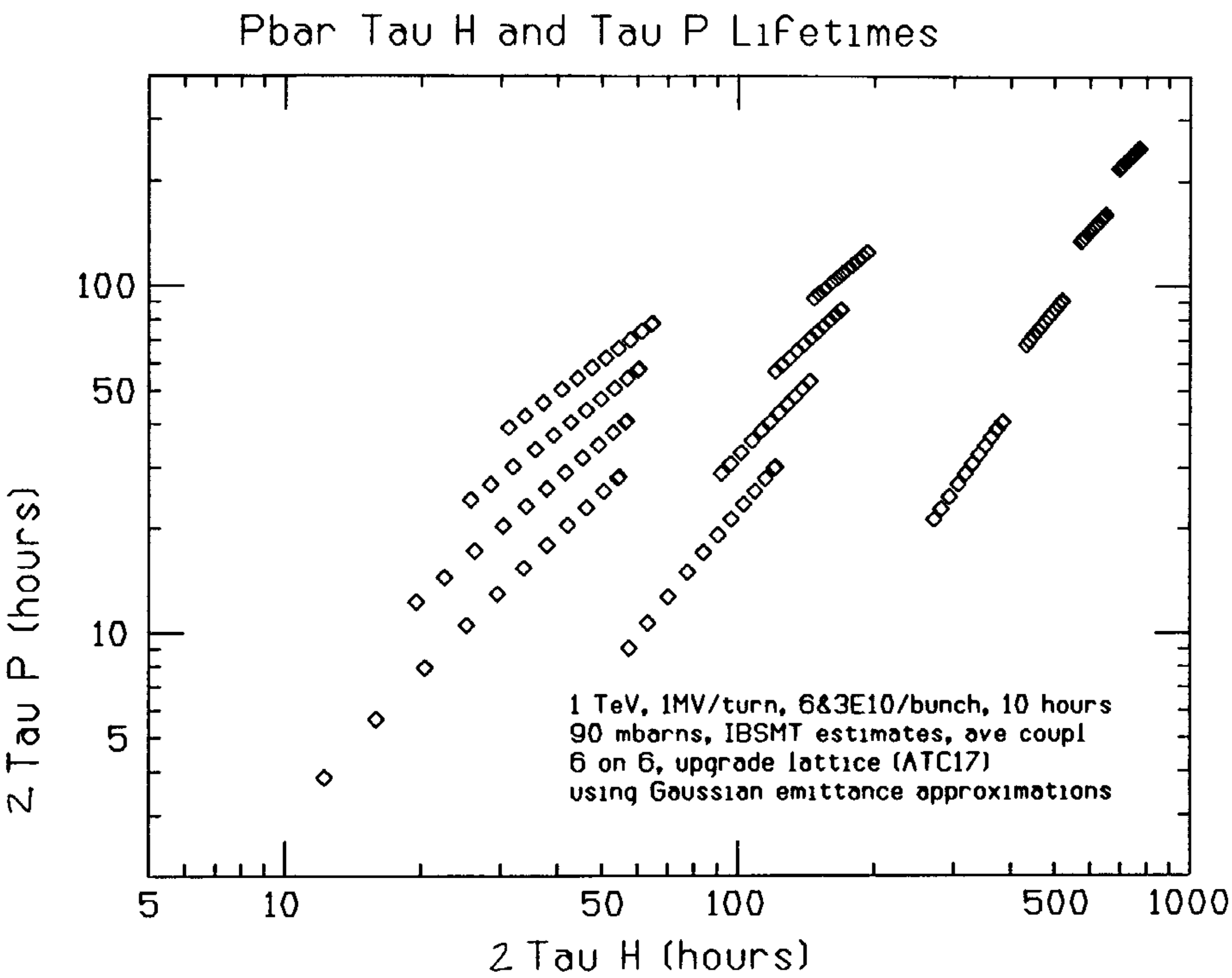

Pbar Tau H and Tau P Lifetimes
2 Tau P (hours)
100
50
10
5
5
10
50
100
500
1000
2 Tau H (hours)
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC17)
using Gaussian emittance approximations

Figure 8d

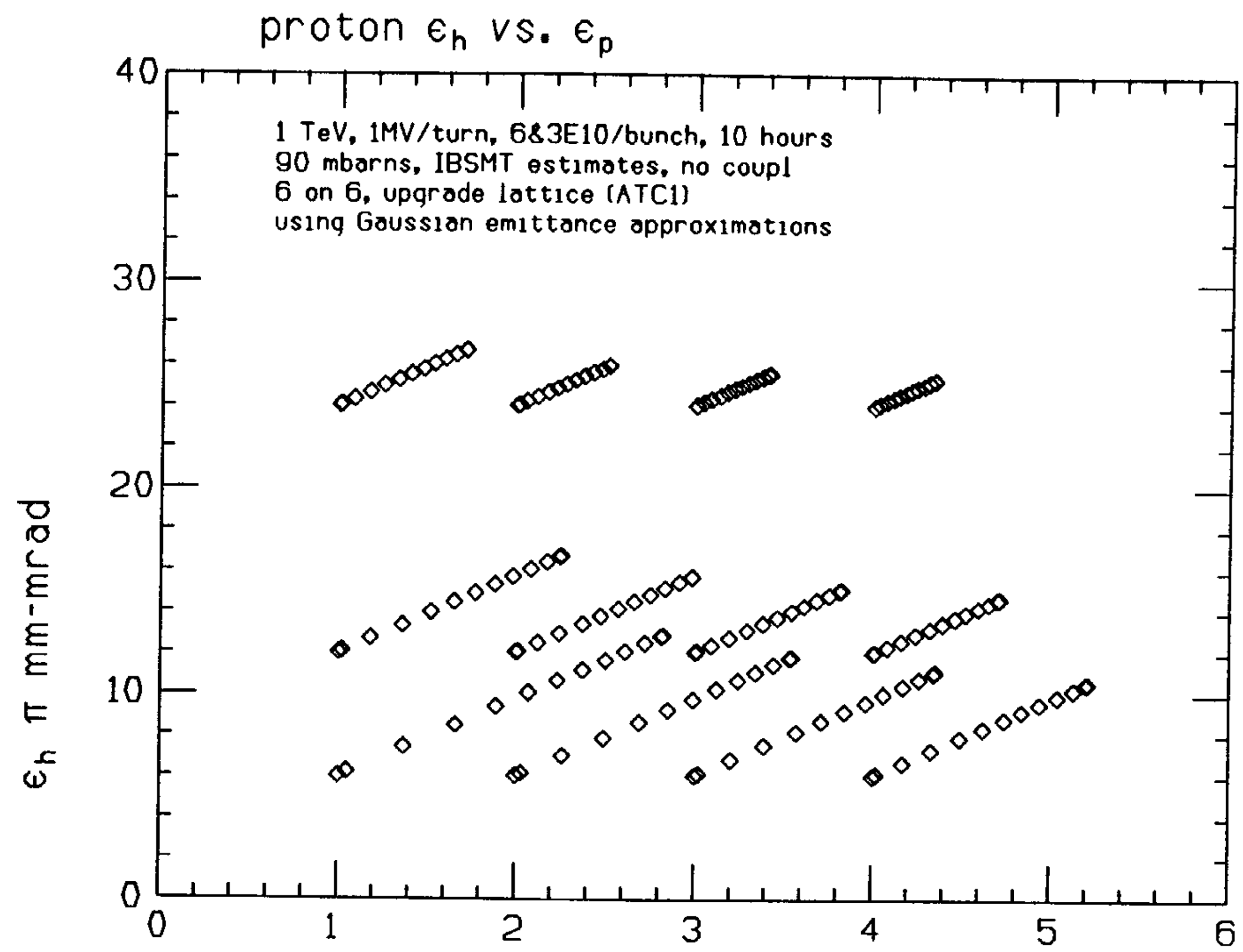

proton ϵ_h vs. ϵ_p
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
ϵ_h π mm-mrad
ϵ_p eV-sec
0
10
20
30
40
0
1
2
3
4
5
6

Figure 9a

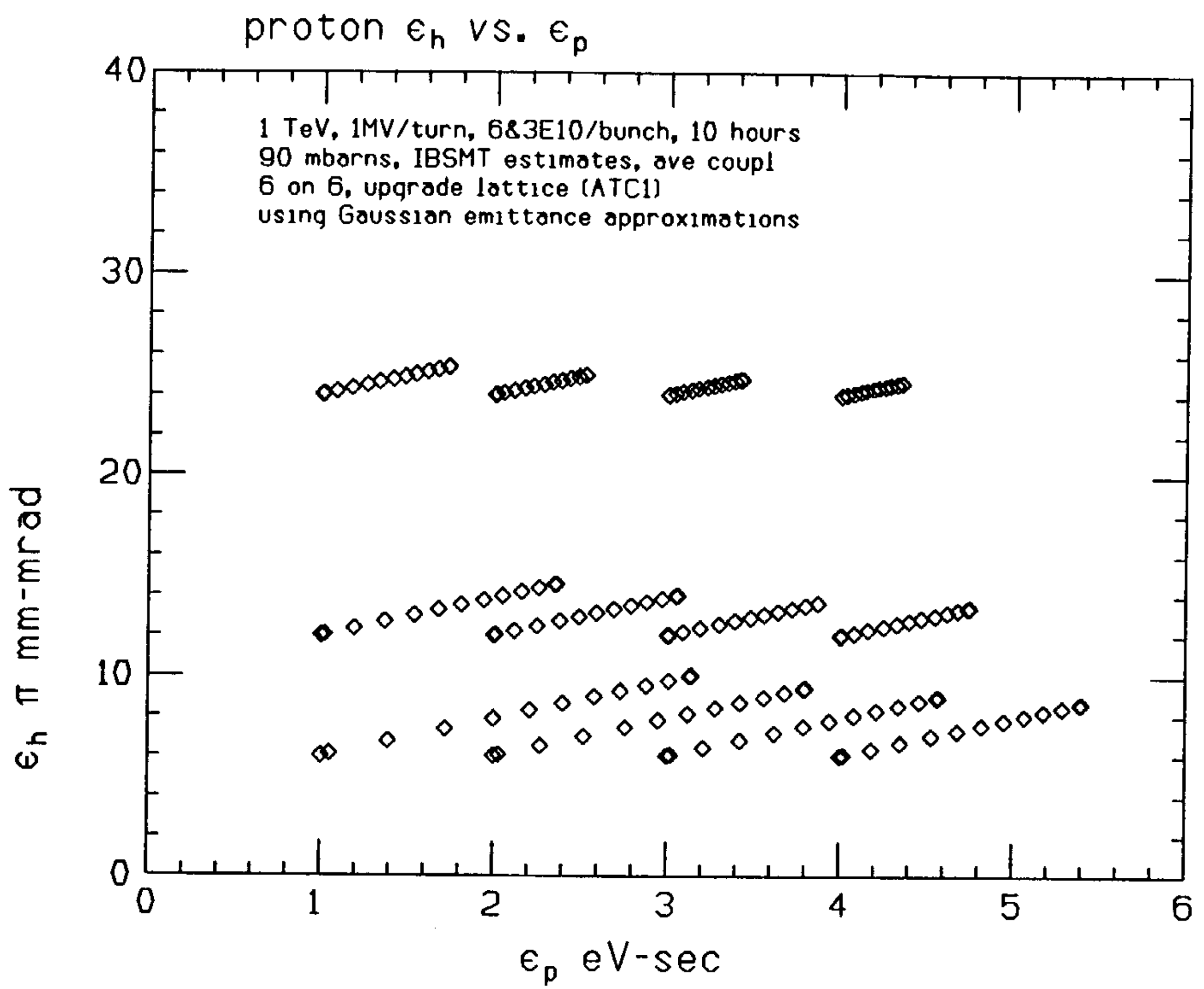
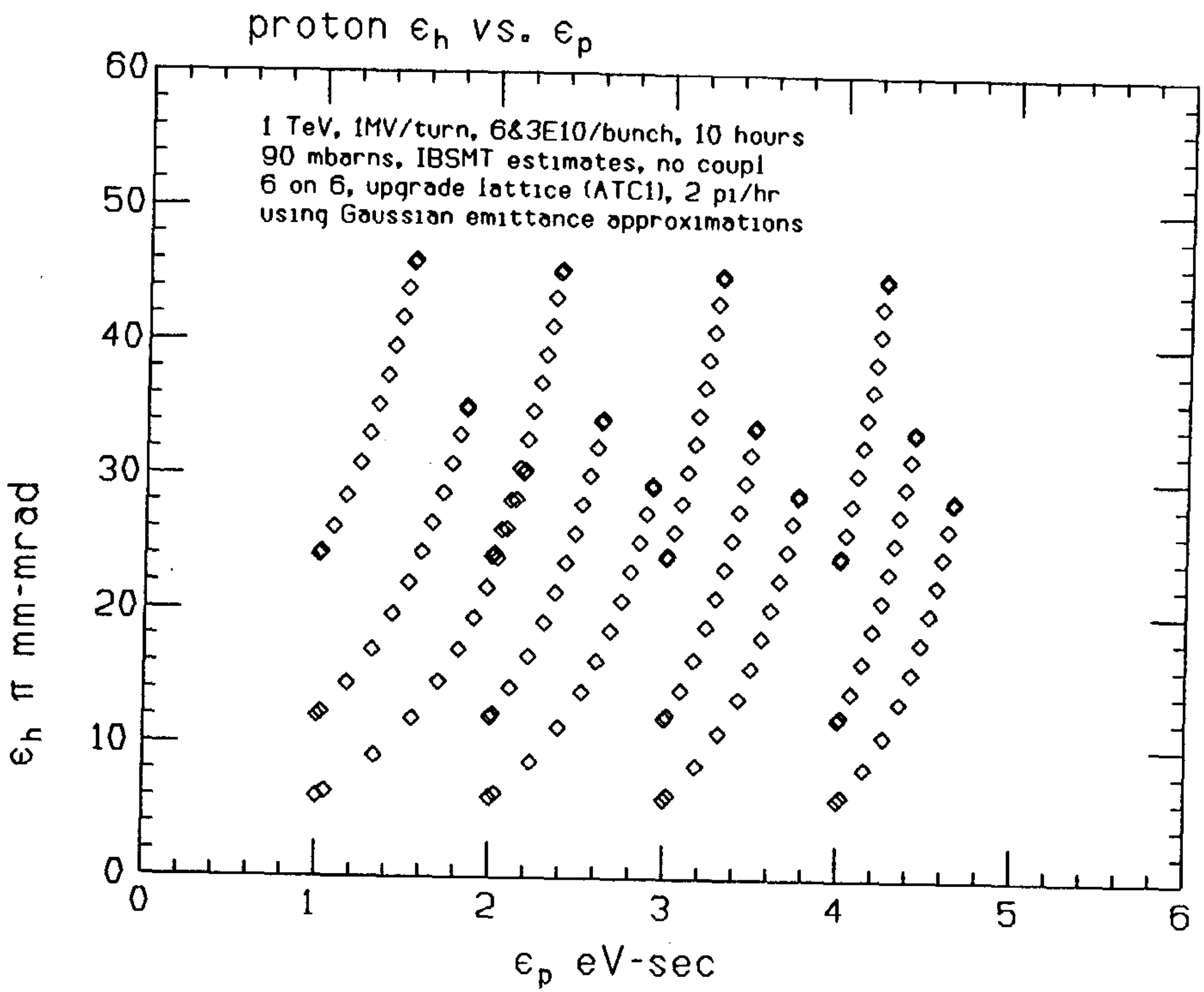

proton ϵ_h vs. ϵ_p
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
40
30
20
10
0
0
1
2
3
4
5
6
ϵ_h π mm-mrad
ϵ_p eV-sec

Figure 9b


proton ϵ_h vs. ϵ_p
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1), 2 pi/hr
using Gaussian emittance approximations
ϵ_h π mm-mrad
0
10
20
30
40
50
60
0
1
2
3
4
5
6
ϵ_p eV-sec
Figure 9c

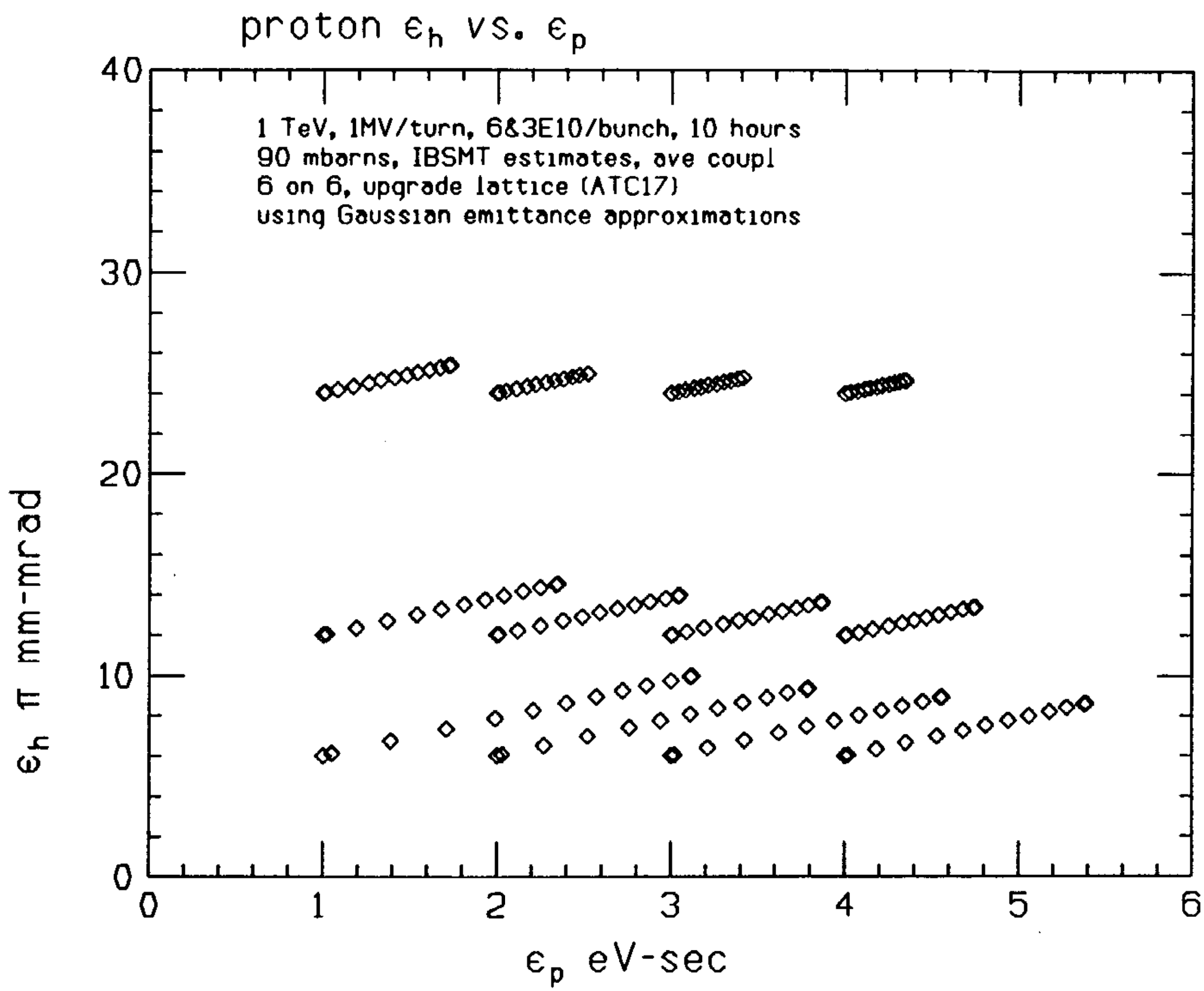
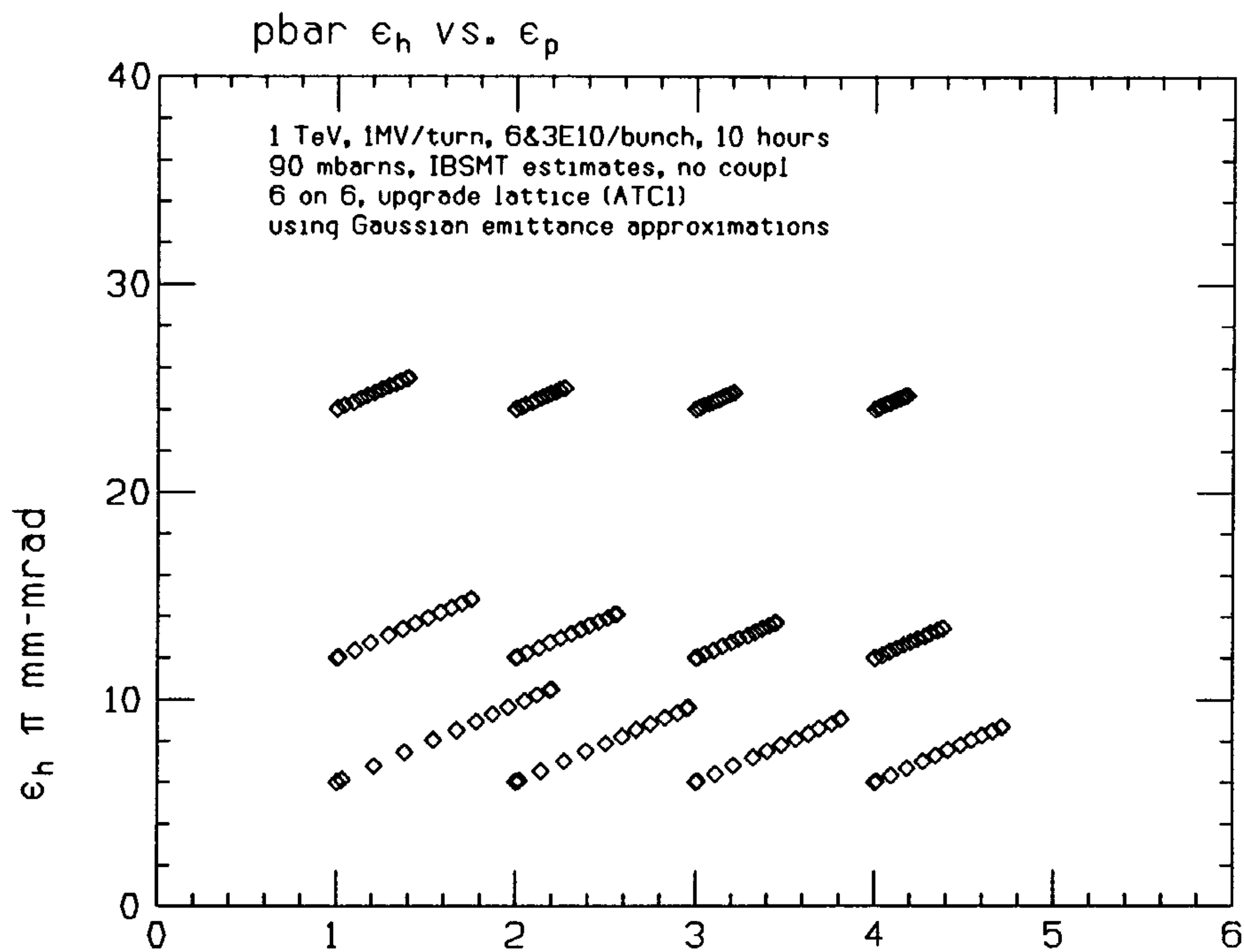

proton ϵ_h vs. ϵ_p
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC17)
using Gaussian emittance approximations
ϵ_h π mm-mrad
0
10
20
30
40
0
1
2
3
4
5
6
ϵ_p eV-sec

Figure 9d



pbar ϵ_h vs. ϵ_p
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
ϵ_h π mm-mrad
ϵ_p eV-sec
0
10
20
30
40
1
2
3
4
5
6

Figure 10a

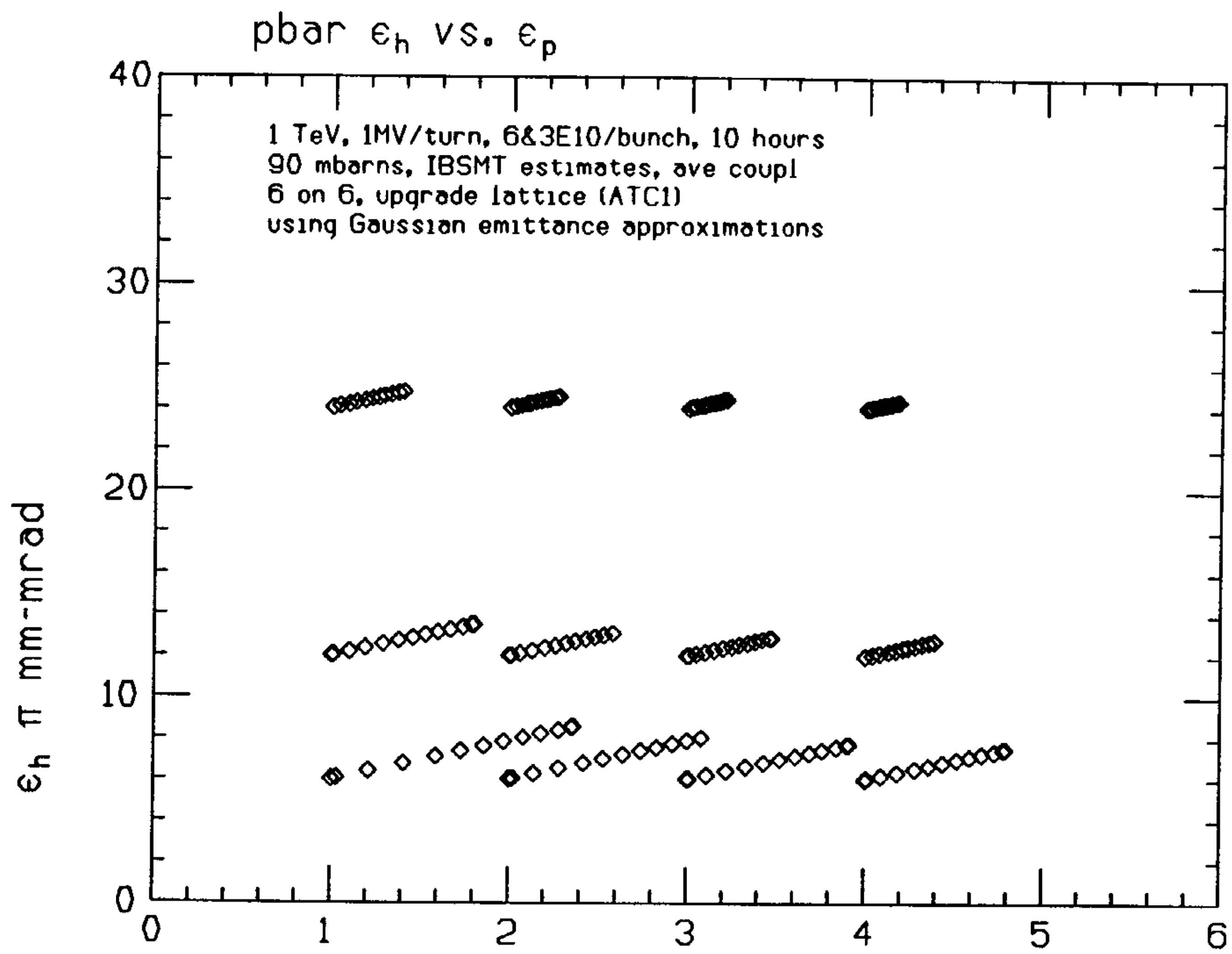
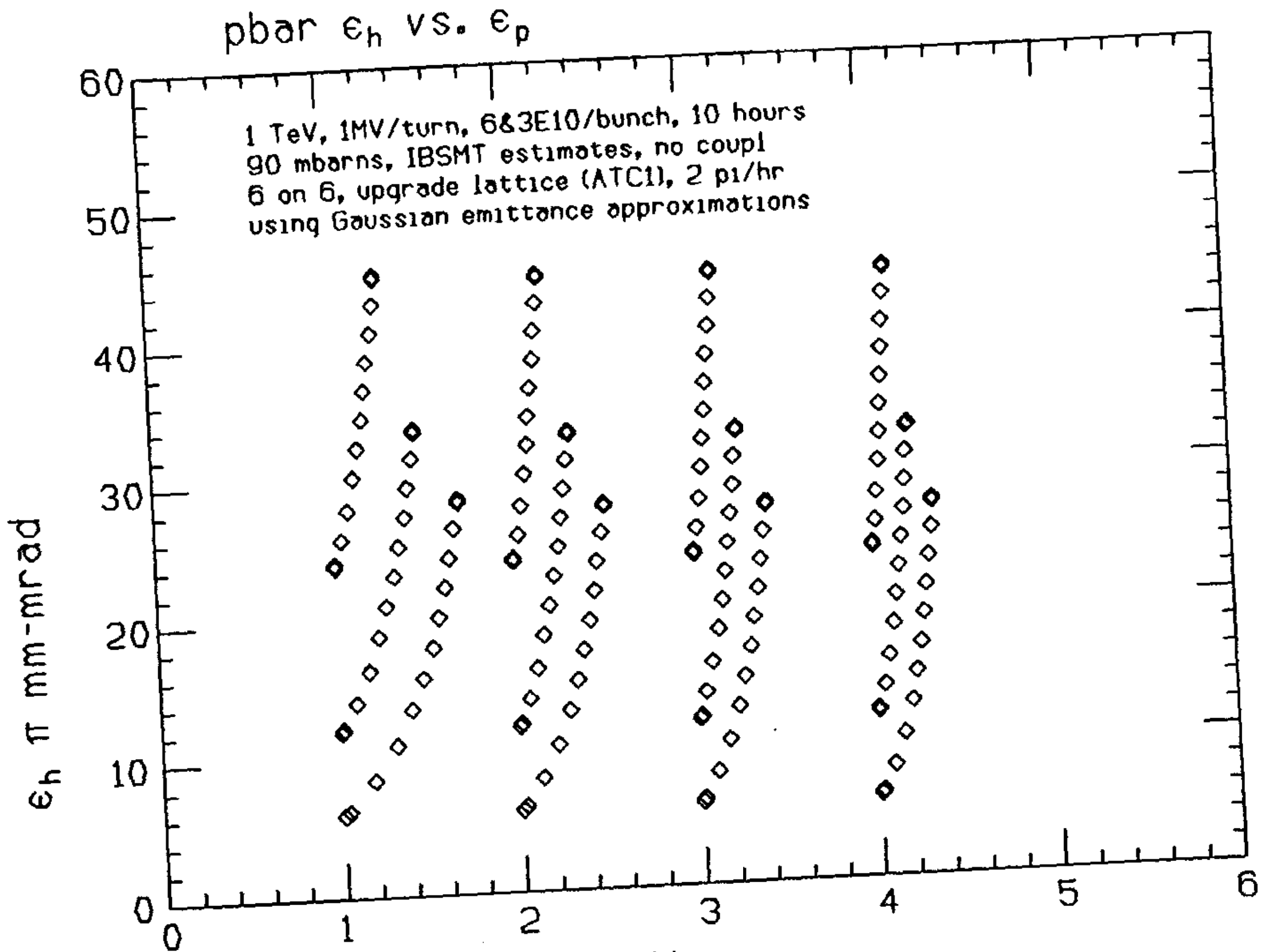
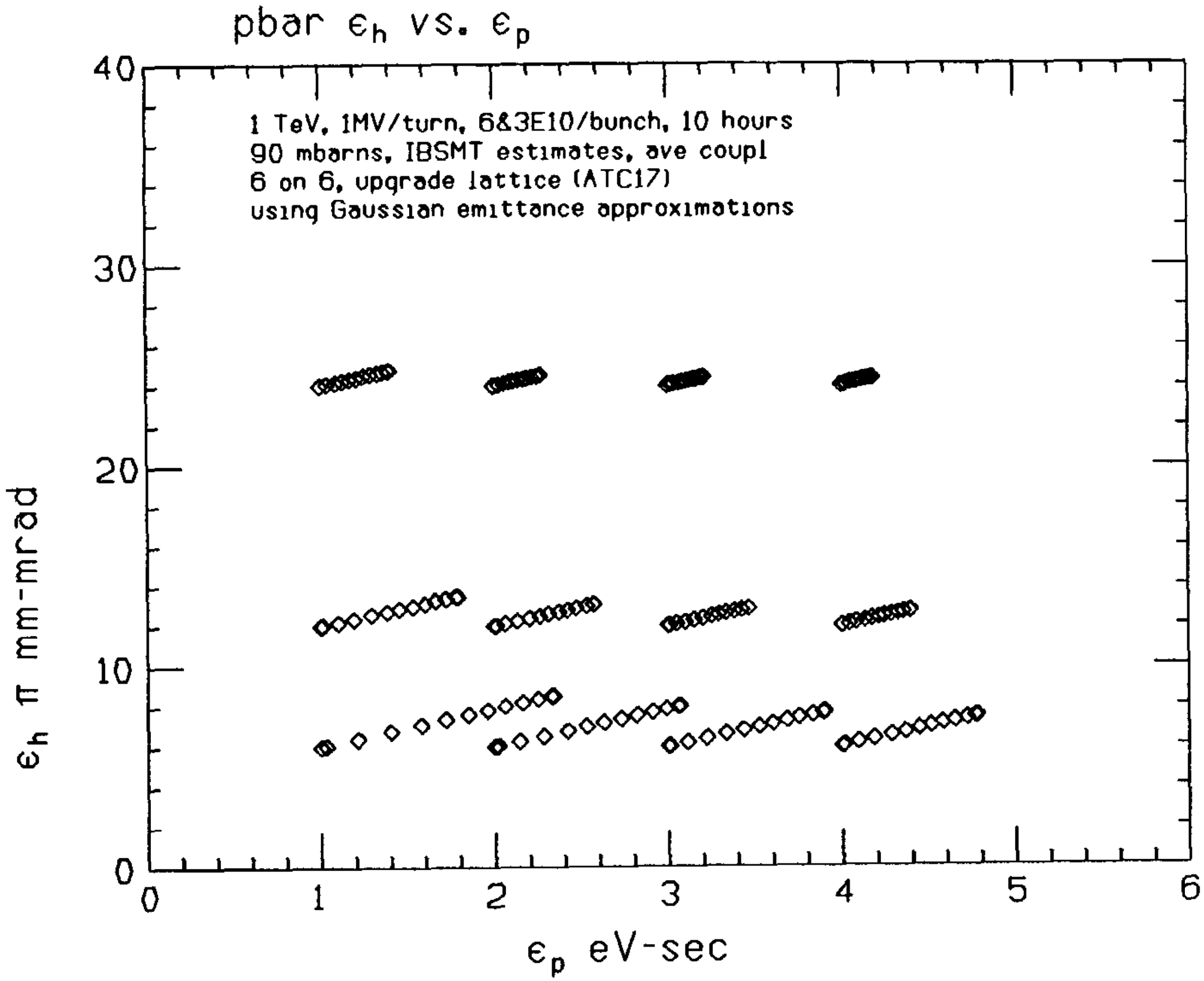

pbar ϵ_h vs. ϵ_p
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC1)
using Gaussian emittance approximations
ϵ_h π mm-mrad
ϵ_p eV-sec
0
10
20
30
40
0
1
2
3
4
5
6

Figure 10b



pbar ϵh vs. ϵp
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, no coupl
6 on 6, upgrade lattice (ATC1), 2 pi/hr
using Gaussian emittance approximations
ϵh π mm-mrad
ϵp eV-sec
0
10
20
30
40
50
60
1
2
3
4
5
6

Figure 10c



pbar ϵ_h vs. ϵ_p
1 TeV, 1MV/turn, 6&3E10/bunch, 10 hours
90 mbarns, IBSMT estimates, ave coupl
6 on 6, upgrade lattice (ATC17)
using Gaussian emittance approximations
ϵ_h π mm-mrad
ϵ_p eV-sec

Figure 10d

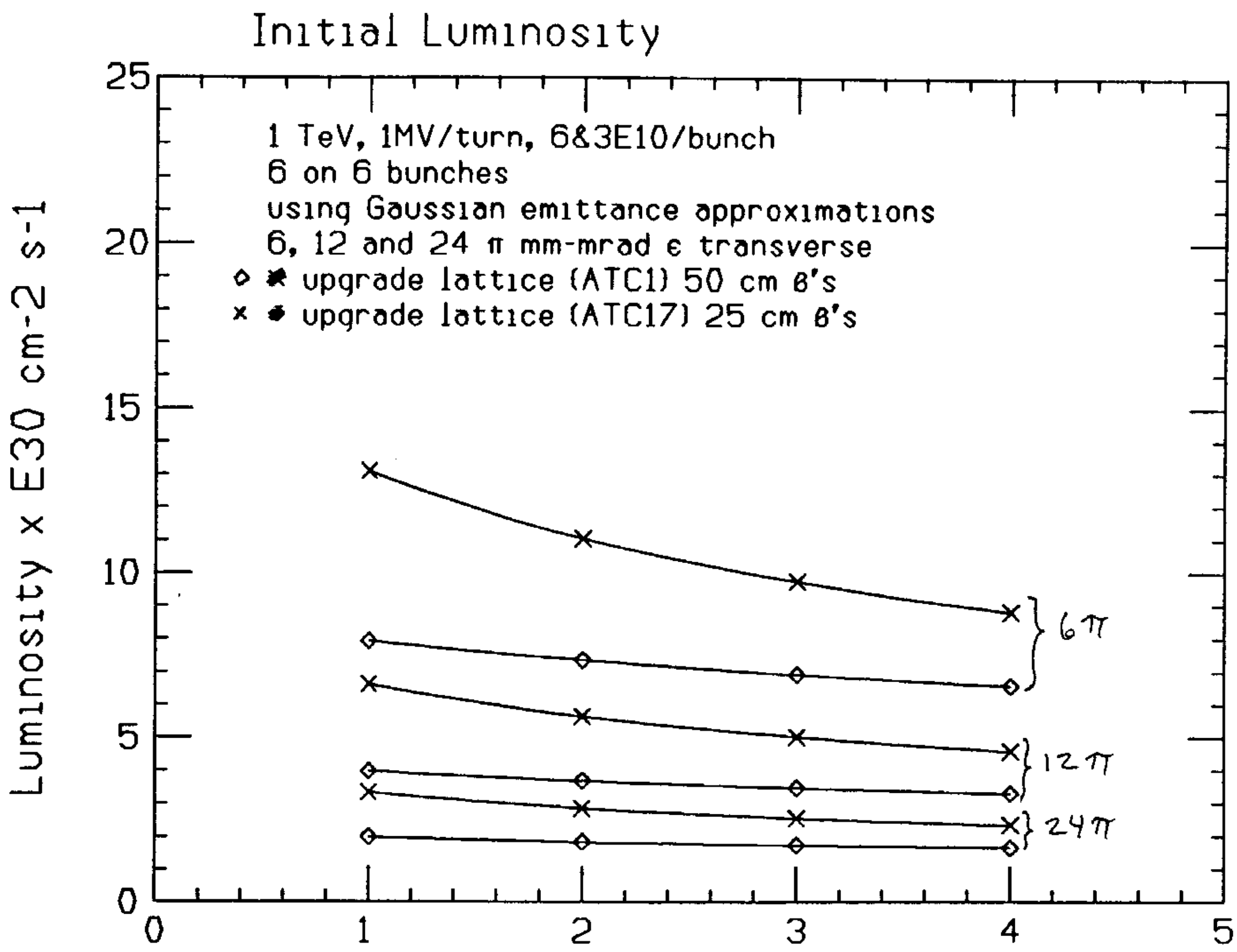
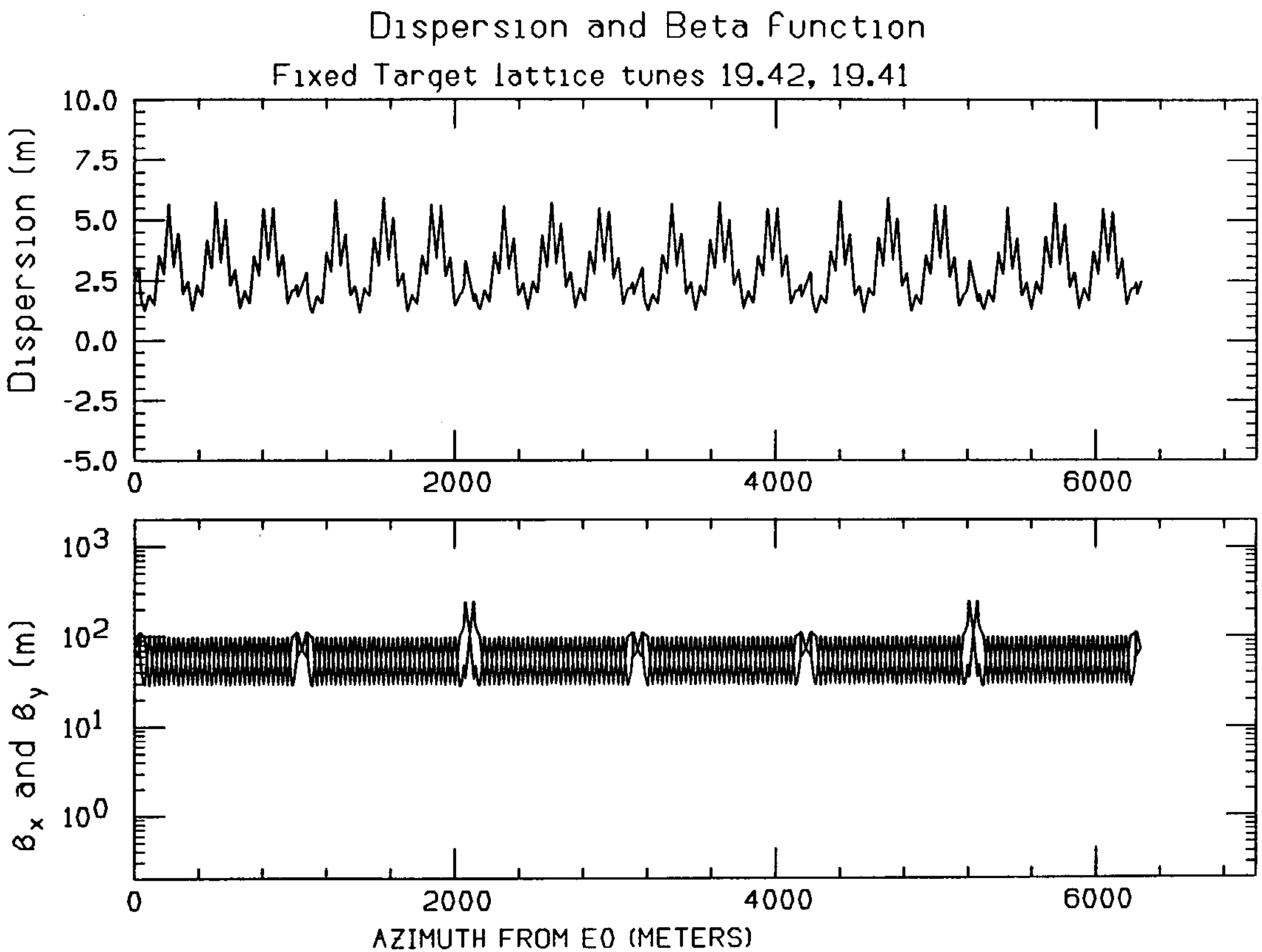

Initial Luminosity
1 TeV, 1MV/turn, 6&3E10/bunch
6 on 6 bunches
using Gaussian emittance approximations
6, 12 and 24 π mm-mrad ε transverse
◇ ✱ upgrade lattice (ATC1) 50 cm β's
× ● upgrade lattice (ATC17) 25 cm β's
6π
12π
24π
Luminosity x E30 cm-2 s-1
0
5
10
15
20
25
0
1
2
3
4
5
εp eV-sec

Figure 11



Dispersion and Beta function
Fixed Target lattice tunes 19.42, 19.41
Dispersion (m)
10.0
7.5
5.0
2.5
0.0
-2.5
-5.0
0
2000
4000
6000
β_x and β_y (m)
10^3
10^2
10^1
10^0
0
2000
4000
6000
AZIMUTH FROM E0 (METERS)

Figure 12a

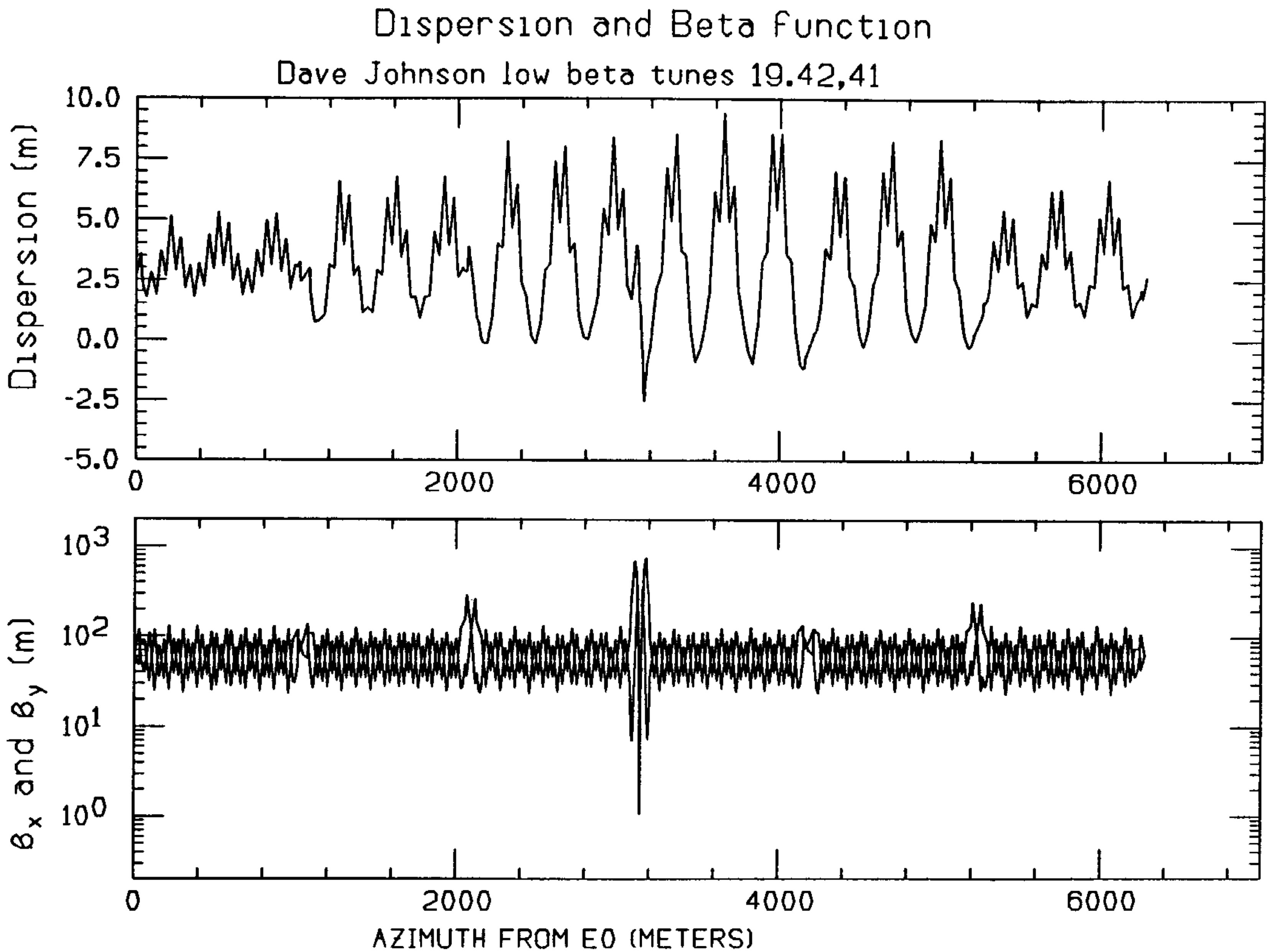

Dispersion and Beta function
Dave Johnson low beta tunes 19.42,41
Dispersion (m)
10.0
7.5
5.0
2.5
0.0
-2.5
-5.0
0
2000
4000
6000
β_x and β_y (m)
10^3
10^2
10^1
10^0
0
2000
4000
6000
AZIMUTH FROM E0 (METERS)

Figure 12b

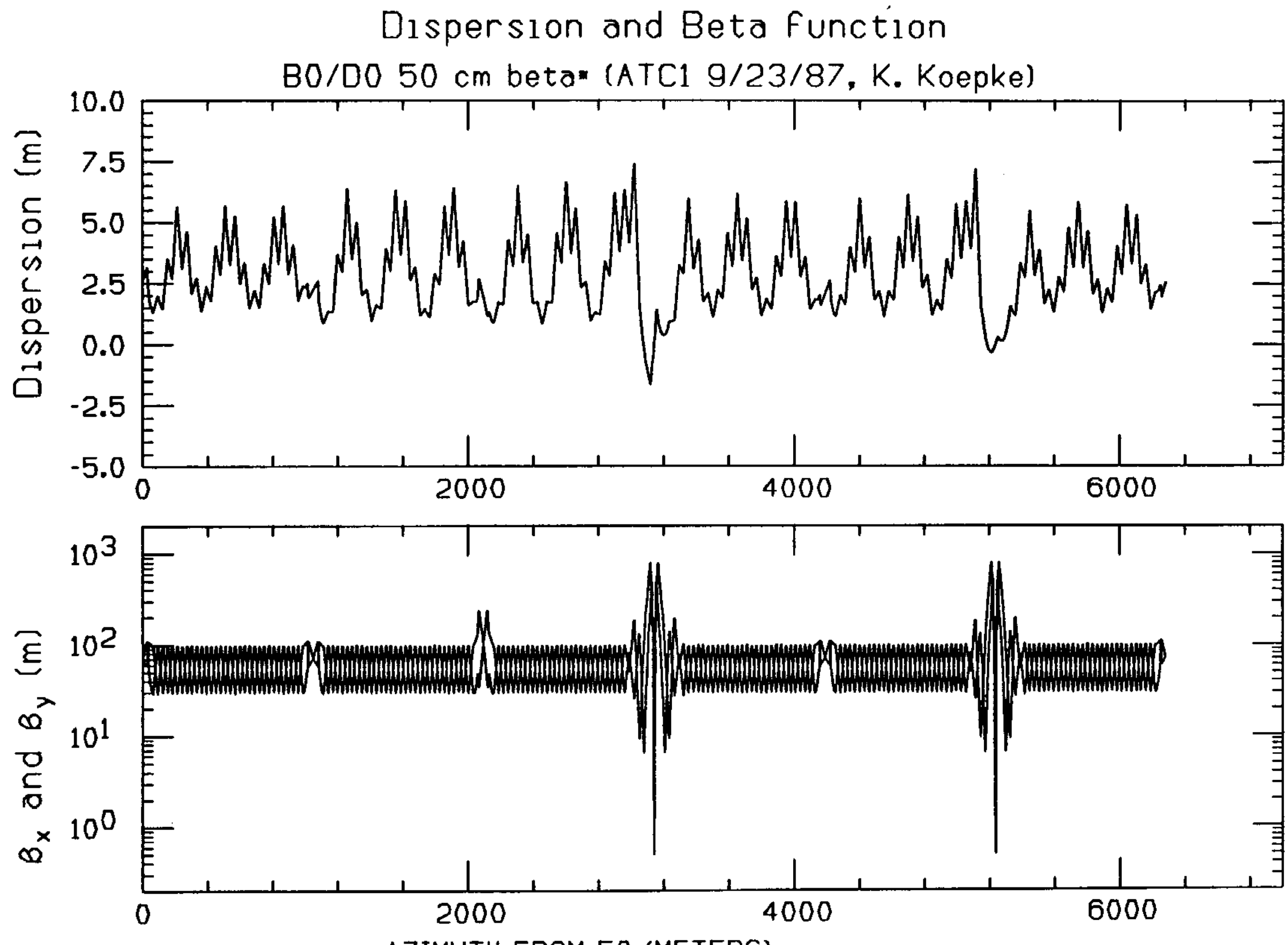
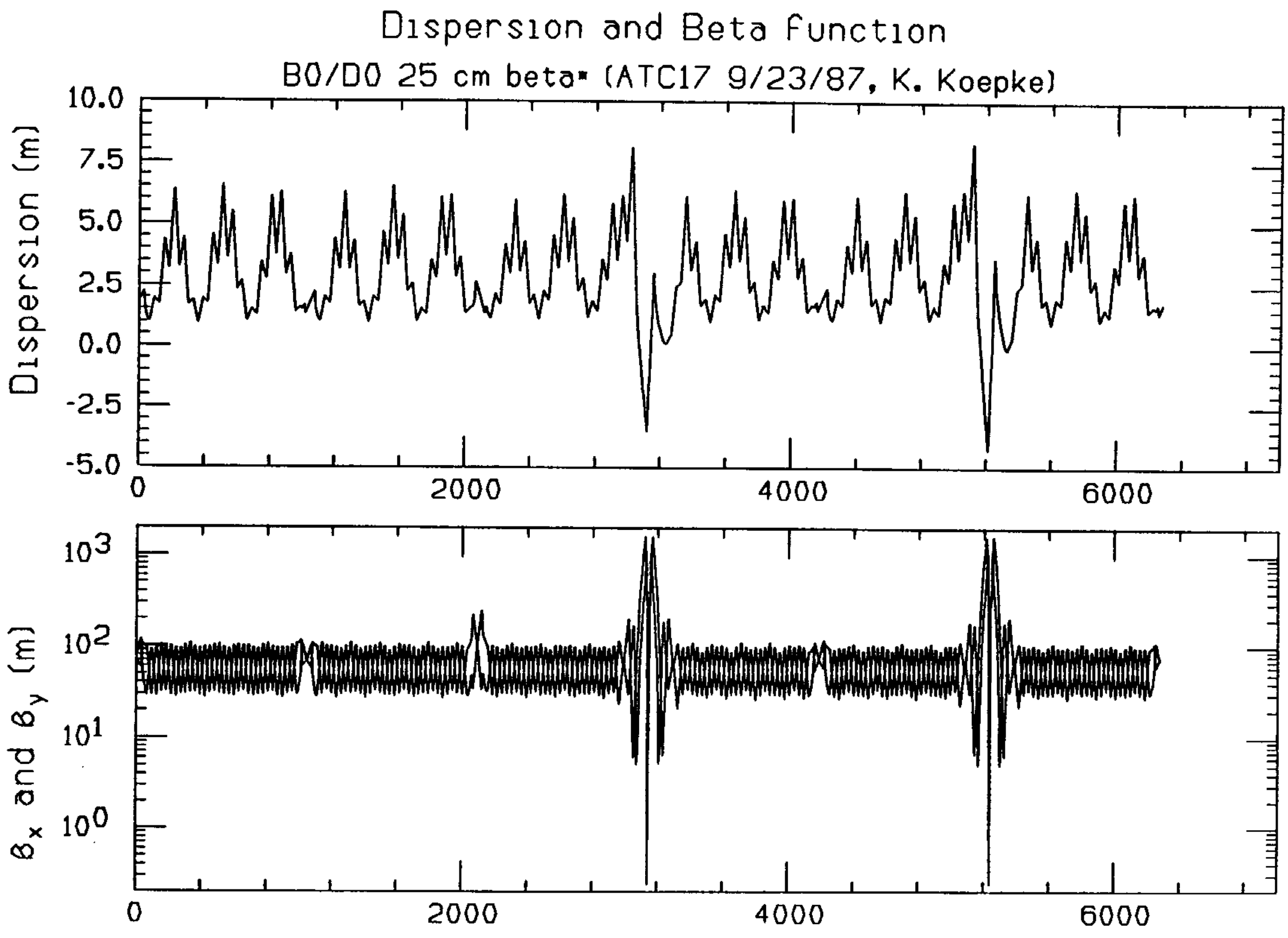

Dispersion and Beta function
B0/D0 50 cm beta* (ATC1 9/23/87, K. Koepke)
Dispersion (m)
10.0
7.5
5.0
2.5
0.0
-2.5
-5.0
0
2000
4000
6000
β_x and β_y (m)
10^3
10^2
10^1
10^0
0
2000
4000
6000
AZIMUTH FROM E0 (METERS)

Figure 12c



Dispersion and Beta Function
B0/D0 25 cm beta* (ATC17 9/23/87, K. Koepke)
Dispersion (m)
10.0
7.5
5.0
2.5
0.0
-2.5
-5.0
0
2000
4000
6000
β_x and β_y (m)
10^3
10^2
10^1
10^0
AZIMUTH FROM E0 (METERS)

Figure 12d

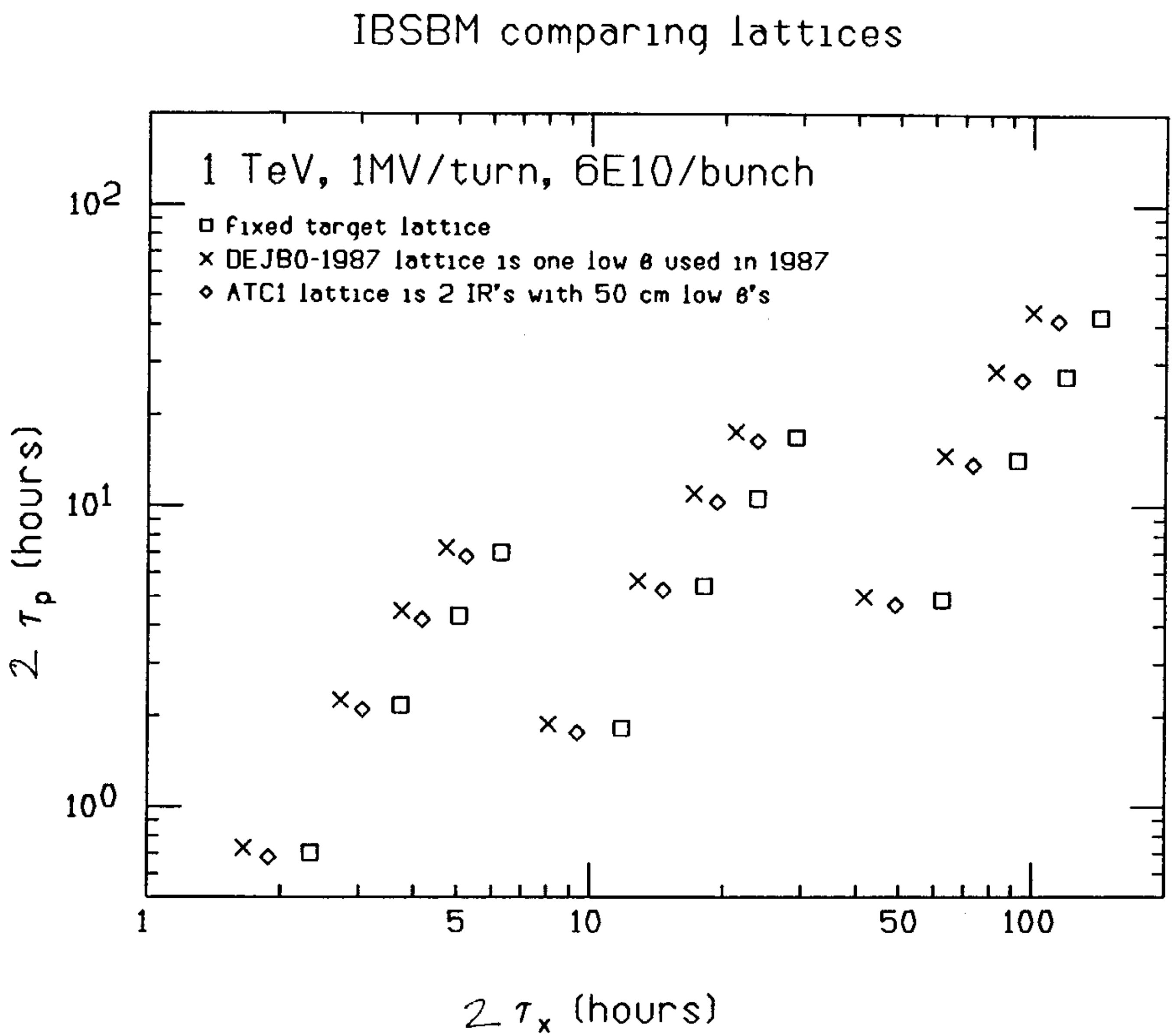

IBSBM comparing lattices
1 TeV, 1MV/turn, 6E10/bunch
□ fixed target lattice
× DEJB0-1987 lattice is one low β used in 1987
◇ ATC1 lattice is 2 IR's with 50 cm low β's
10^2
10^1
10^0
$2\ \tau_p$ (hours)
1
5
10
50
100
$2\ \tau_x$ (hours)

Figure 13

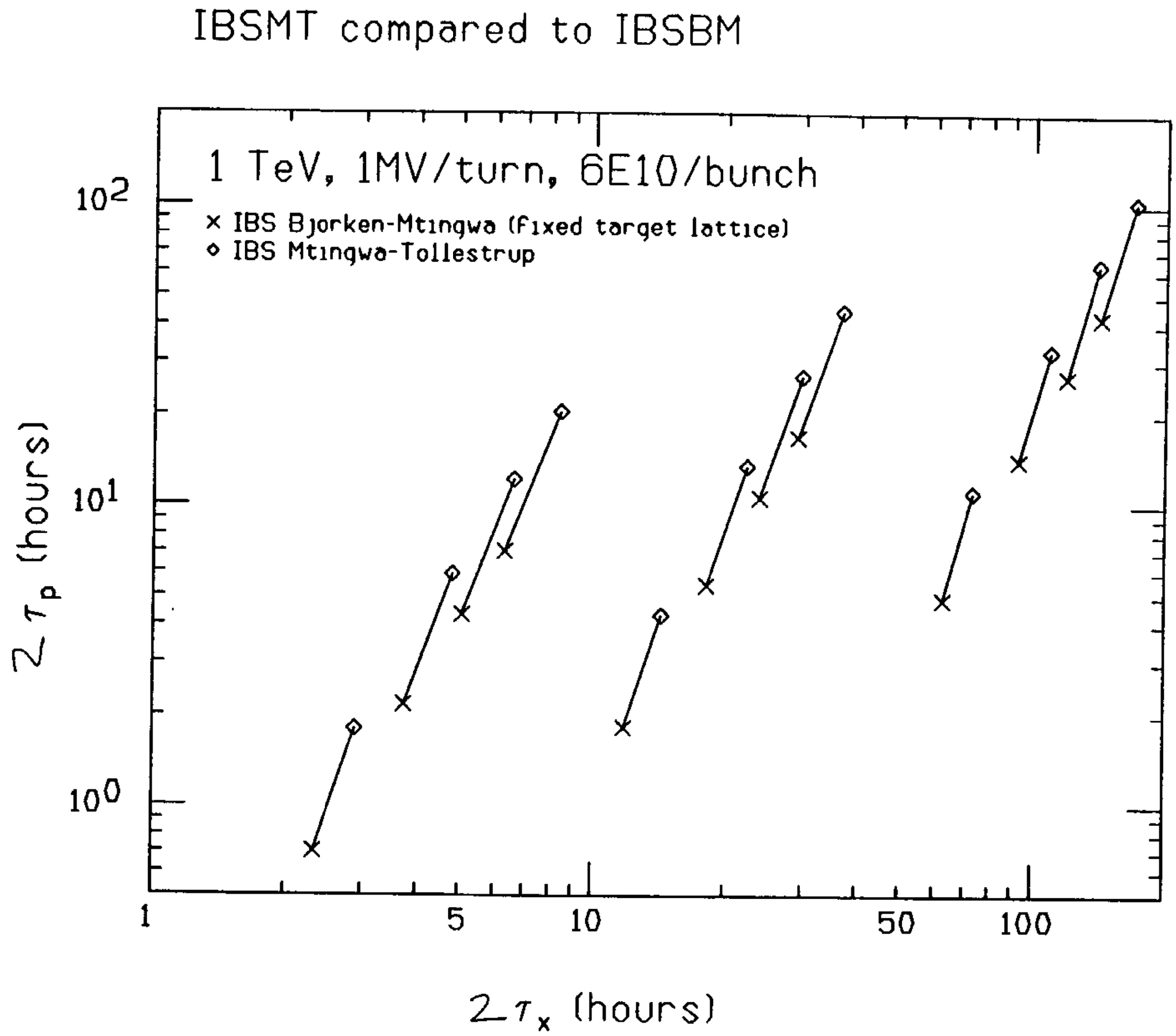

IBSMT compared to IBSBM
1 TeV, 1MV/turn, 6E10/bunch
× IBS Bjorken-Mtingwa (fixed target lattice)
◇ IBS Mtingwa-Tollestrup
10^2
10^1
10^0
1
5
10
50
100
$2\tau_p$ (hours)
$2\tau_x$ (hours)

Figure 14